VOLUME LIV NUMBER 4

THE JOURNAL OF GEOLOGY

July 1946

MARINE SOLUTION BASINS[1]

K. O. EMERY[2]

Scripps Institution of Oceanography, La Jolla, California

ABSTRACT

High-tide rock basins common in calcareous rocks at La Jolla and elsewhere are described. Rock and water analyses were made in order to determine the origin of the basins. The evidence indicates that biochemical processes cause the sea water in the basins to become unsaturated with calcium carbonate at night, so that calcite cement is dissolved from the rock floor. Waves at high tide and snails living in the basins remove the uncemented rock grains. During the daytime, however, the water deposits calcium carbonate, and for the higher tide pools this deposition results in greater induration of the rock at the edge of the pools, so that resistant elevated rims are formed.

INTRODUCTION

In 1937 the author became interested in the very numerous tide pools in sandstone benches along the coast at La Jolla, California. Even casual inspection of the tide-pool basins indicates a complex origin. The shape and other characteristics show that they are in part due to solution of the rock. Solution of the calcium carbonate cement in the sandstone, however, is not a complete explanation, because the solvent, sea water, is normally saturated with $CaCO_3$. Moreover, many of the basins are surrounded by elevated rims, features suggestive of deposition rather than of solution. When opportunities presented themselves, during vacations and holidays, an investigation of the origin of the basins was made.

[1] *Contributions from the Scripps Institute of Oceanography*, N.S., No. 293.

[2] Now at Geology Department, University of Southern California, Los Angeles, California.

DISTRIBUTION AND PREVIOUS THEORIES OF ORIGIN

At La Jolla and Point Loma, California, the basins occur in sandstones of the Cretaceous Chico formation and Eocene Rose Canyon formation. The author has seen similar basins in a limestone member of the Miocene Altamira formation near San Pedro, California; in Pliocene[3] shell limestone at Cedros Island, Baja California, Mexico; in Tertiary coral limestone at Key West, Florida; in a Tertiary calcareous sandstone at San Juan, Puerto Rico; and in Pleistocene calcareous eolianite and marine limestone at Bermuda.

The basins in Bermuda were photographed and briefly described by R. W. Sayles as due to solution.[4] Basins in sand-

[3] The age was determined from enclosed fossils by Dr. B. F. Osorio Tafall (personal communication).

[4] "Bermuda during the Ice Age," *Contr. Bermuda Biol. Sta. Res.*, No. 165 (1931), Pl. 10, pp. 404, 405.

stone on the coasts of Morotai and Wotap islands, like those of Figure 3, were ascribed by P. H. Kuenen[5] to the crystallization of salt around the edges of pools of water, thus indurating that part of the rock, so that later erosion produced rimmed basins. Similar basins in limestone were described from the coastal benches of Hawaii by C. K. Wentworth,[6] who believed them due to solution by fresh water from rain or ground water. Isabel Henkel[7] suggested that basins in sandstone of Vancouver Island, Canada, somewhat like those of Figures 3 and 5, are developed by a wide variety of processes, chief of which is the weathering-out of concretions, which serve as abrasive tools to form potholes. Rimmed basins on Triassic sandstone marine benches of Australia were photographed by J. T. Jutson,[8] who offered no explanation of them. Others have been noted on Ulithi Atoll and New Guinea.[9]

Some basins found on land at considerable distance from shore possess characteristics like those of the marine basins and are believed due to solution. Such basins in limestone were described by Wentworth[10] from the interior of Hawaii. Smith and Albritton[11] found shallow basins, called *tinajitas*, in Cretaceous limestones of western Texas, which they believed resulted from solution by occasional rains and flushing of the residue by exceptionally heavy rains or by winds.

Even igneous rocks contain basins probably due to solution. F. S. Matthes[12] described basins about 45 cm. in diameter in granite and quartz monzonite of the Sierra Nevada, which he thought were formed by solution of less resistant minerals by rain water acidified by decomposing pine needles and other vegetation. Freezing water assists by loosening grains or flakes of the rock. Larger basins in granite of South Carolina are ascribed by L. L. Smith[13] to accelerated weathering by acids from the decomposition of vegetation. Water of the basins has a low pH and gives a strong test for sulphur dioxide, hydrogen sulphide, and carbon dioxide. The author also has seen similar basins up to 2 meters in diameter in granite at Elephant Rocks, Missouri. Basins described as potholes by M. B. Fuller[14] occur in schist in Colorado, but photographs show that some of the smaller ones are shallow and flat bottomed, unlike ordinary potholes; and it is possible that these particular basins are due to solution. That water containing CO_2 is competent to dissolve minerals of igneous and metamorphic rocks has been shown by several workers.[15]

[5] "Einige Bilder Eigentümlicher Verwitterungsformen an tropischen Küsten (Molukken)," *Geologie der Meere und Binnengewässer*, Vol. I (1937), pp. 22–26.

[6] "Potholes, Pits, and Pans: Subaerial and Marine," *Jour. Geol.*, Vol. LII (1944), pp. 117–30.

[7] "A Study of Tide-Pools on the West Coast of Vancouver Island," *Postelsia: The Yearbook of the Minnesota Seaside Station* (1906), pp. 277–304.

[8] "Shore Platforms near Sydney, New South Wales," *Jour. Geomorph.*, Vol. II (1939), pp. 237–50.

[9] W. H. Easton, James Gilluly, W. C. Putnam, personal communications.

[10] *Idem.*

[11] J. F. Smith, Jr., and C. C. Albritton, Jr., "Solution Effects on Limestone as a Function of Slope," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 61–78.

[12] "Geologic History of the Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), p. 64, Pl. 33.

[13] "Weather Pits in Granite of the Southern Piedmont," *Jour. Geomorph.*, Vol. IV (1941), pp. 117–27.

[14] "The Bearing of Some Remarkable Potholes on the Early Pleistocene Glaciation of the Front Range, Colorado," *Jour. Geol.*, Vol. XXXIII (1925), pp. 224, 225.

[15] Richard Müller, "Untersuchungen über die Einwirkung des Kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine," *Tschermak Min. Mittheil.*, Vol. VII (1877), pp. 25–48.

DESCRIPTION OF BASINS

RELATION TO TIDE

Near La Jolla, tide-pool basins are very well developed along 2 km. of the coast where a bench of Cretaceous sandstone slopes gently toward the sea. The basins are within the area exposed at mid-tide beyond the foot of a low sea cliff which is reached by only the very highest tides. A cross-sectional strip near Whale View Point, extending the 30 meters distance from the cliff across and beyond the bench to the mid-tide line and having a width of 6 meters, was selected for a quantitative study of the basins. The 30-meter length of the strip was divided into ten zones, each 3 meters by 6 meters in dimensions. All basins of each zone were counted and measured, with results as shown in Figure 1.

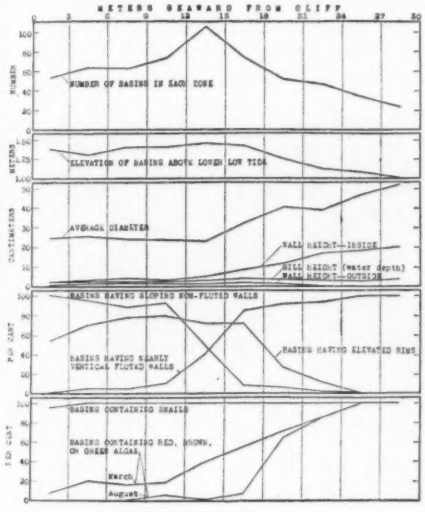

FIG. 1.—Variation of elevation, number, diameter, depth, and other characteristics of solution basins found in ten zones extending from a sea cliff to the mid-tide line 30 meters seaward.

The elevation of the basins ranges from 1.45 meters above mean lower low tide near the outer part of the bench to 1.00 meter in the zone farthest seaward beyond the bench. For comparison, at La Jolla, the mean tide range is 1.10 meters, with mean high tide about +1.45 meters and mean low tide about +0.35 meter above mean lower low tide. However, extreme tides of +2.30 meters and −0.55 meter occur during the year.[16] The tide

FIG. 2.—Renewal of sea water in basins at high tide.

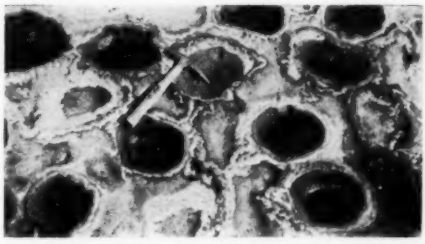

FIG. 3.—Basins characteristic of 9–12-meter zone, showing sea salt deposited from evaporation of water after a warm day of low tides (May, 1944).

range is sufficient to cause a daily and sometimes a semidaily refilling of all the basins (Fig. 2) except during calm neap-tide periods, when the highest basins may not be refilled for several days, so that their content of water may entirely evaporate, as in Figure 3.

SIZE AND SHAPE

As shown by Figure 1, the basins are most numerous on the higher parts of

[16] "Tide Tables, Pacific Ocean and Indian Ocean for the Year 1944," *U.S. Coast and Geod. Surv.*, Serial No. 653, pp. 66–69, 275.

the bench in the 9–18-meter zones, which contain mostly the type illustrated in Figure 4. Shoreward the basins are fewer in number, presumably because of being in an earlier stage of development. Seaward they are less abundant because of their larger diameter, resulting partly

FIG. 4.—Basins characteristic of 15–18-meter zone. Note presence of elevated rims and relatively flat bottoms. Rims are covered by evaporating water drawn by capillarity from the basins (January, 1944).

FIG. 5.—Basin of 18–21-meter zone representing the coalescence of at least four basins. Note the elevated rims having vertical fluted inner walls and the presence of snails within some of the flutings (January, 1944).

from the coalescence of adjacent basins (Fig. 5). Figure 1 shows that, as the diameter increases, the depth of the basin below the top of its surrounding wall also becomes greater, so that the basins farthest seaward are both broadest and deepest. However, it should be noted that, in spite of the greater inside wall height of the seaward basins, the depth of water which they can retain is not much greater than that for the shallower basins landward. This apparently is due to downcutting of their outlets, as illustrated in Figure 6.

Most of the landward basins are nearly circular in outline; but many of those farther seaward are very irregular, having shapes indicative of the coalescence of several smaller basins.

An outstanding feature of the top of the bench is the presence of volcano-like elevated rims surrounding the basins, as shown in Figures 3, 4, and 5. The top of

FIG. 6.—Basins characteristic of the 21–24-meter zone. Note the high vertical fluted walls and the shallow depth of water resulting from the downcutting of the outlets. The elevated rims of basins in zones farther landward are absent (January, 1944).

the rim is usually 2–8 cm. higher than the bottom of the basin, but it may also reach 1–5 cm. above the level of the rock surface outside the basin. In the area studied, the bottom of each rimmed basin lies at a lower level than the surrounding rock surface. The rim is less pronounced in the seaward basins and is rarely present beyond the 15–18-meter zone (Figs. 1 and 6). Another interesting characteristic of the walls of basins on the outer part of the bench and farther seaward is the presence of flutings or shallow vertical concavities extending from the top to the bottom of the inner face of the walls (Figs. 5 and 6). Walls having these flutings are usually nearly vertical. The walls of shoreward basins

rarely show this fluting but, instead, are smoothly rounded and slope gently toward the bottom of each basin (Fig. 3). As shown in Figure 1, practically all the basins in zones from 0 to 12 meters have gently sloping nonfluted walls, while nearly all those from 15 to 30 meters have steep fluted walls.

In other areas near La Jolla, basins have sizes and shapes similar to those discussed; however, basins of some of these areas have no elevated rims (Fig. 7), and in other areas the rims rise as much as 25 cm. above the surrounding

FIG. 7.—Basins having very deep flutings, many of which contain snails. Elevated rims are not present (November, 1943).

rock surface. Most of the examples of very high rims are exceptional and appear to be remnants of the pedestals originally supporting concretions which were weathered out and finally fell away. Elsewhere at La Jolla there are areas of more irregular basins, like those of Figure 8. Basins found at Cedros Island, Bermuda, and Puerto Rico also resembled those of Figure 8, while those at San Pedro were modified by the presence of numerous closely spaced calcite-filled cracks.

Examination of Figure 1 shows that the basins are large in diameter, compared to their depth; and the photographs show that the bottom of most basins is flat. In a few basins, however, rocks have been introduced at some time and have been retained long enough for the basin to develop into a pothole (Fig. 9). These potholes are deep and narrow and have smooth, unfluted, and relatively hard-surfaced walls. Similar transformation of solution basins into

FIG. 8.—Irregular basins in sandstone near the Scripps Institution of Oceanography (August, 1945).

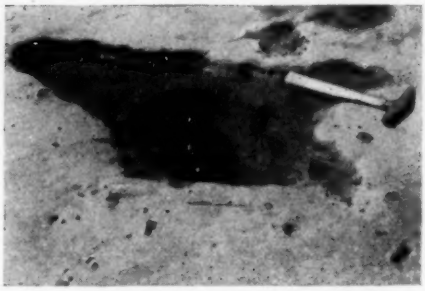

FIG. 9.—Pothole formed in solution basin. Note the smooth deep walls of the pothole and the fluted walls and remnants of the shallow bottom of the original solution basin (July, 1945).

potholes has been noted by E. D. Elston[17] and by Wentworth.[18]

LITHOLOGY

The basins which were most completely studied occur in Cretaceous Chico sandstone. Along the shore the sandstone consists of very gently dipping beds, usually less than 3 meters thick and sepa-

[17] "Potholes: Their Variety, Origin and Significance," *Sci. Monthly*, Vol. V (1916), pp. 554–67; Vol. VII (1918), pp. 37–51.

[18] *Op. cit.*

rated by shale partings. Some contain ripple marks, minor depositional folds, and numerous concretions. Where unweathered, the rock is medium gray and is firmly cemented. Weathered surfaces are dark gray and friable, but too strong to be crushed in the hand. No stains characteristic of weathered pyrite are present. The Eocene Rose Canyon sandstones in which some basins are found have similar lithologic characteristics.

Samples of rock were collected from five basins and investigated for their content of $CaCO_3$. Microscopic examination showed that calcite is present only as cement between detrital sand grains. Percentage of $CaCO_3$ was determined after the samples were crushed and treated with 1 normal hydrochloric acid. Typical results are shown in Figure 10, a scale drawing of the position of rock samples collected from two basins, superimposed on a photograph of one similar typical basin. In general, the highest percentage of $CaCO_3$, 8.8–10.1, was found in samples consisting of scrapings from the walls. The samples scraped from the inner wall were found to have a slightly higher content than those from the outer wall of elevated rims. Samples taken at progressively greater depths within the rims have less cement, 7.9–

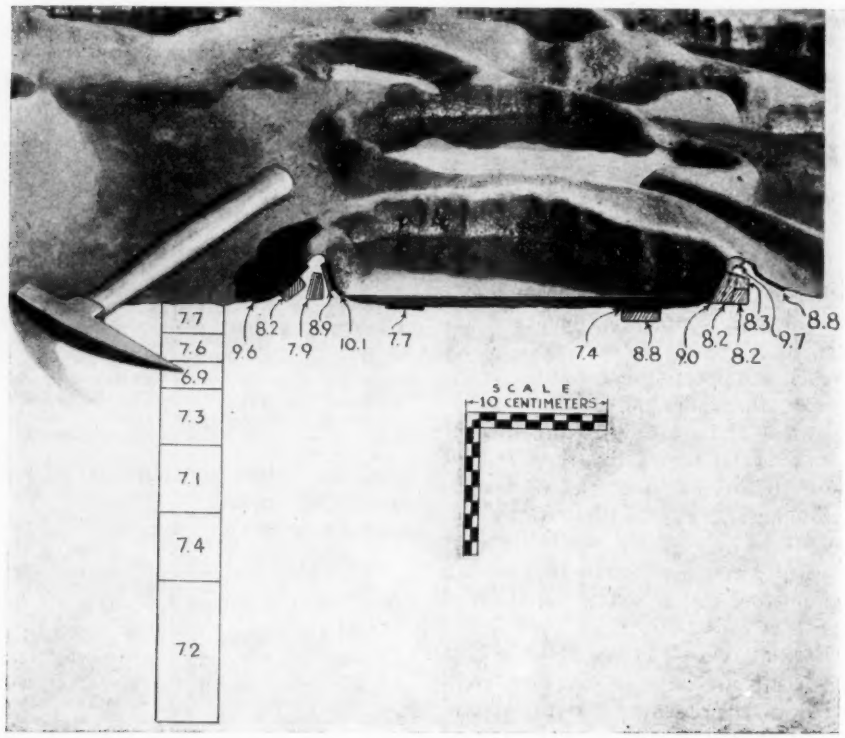

FIG. 10.—Composite photograph and drawing showing the percentage of calcium carbonate in rock samples collected from various parts of two different basins. (Drawn by Mr. Sam Hinton.)

8.3 per cent. For both basins the lowest percentage of $CaCO_3$, 7.4 and 7.7, was found in samples composed of scrapings from the bottom, which is ordinarily covered by water. A hole, drilled to a depth of 30 cm. outside one of the basins and 20 cm. from the rim, yielded samples

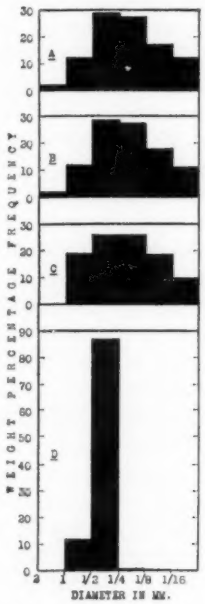

FIG. 11.—Histograms showing size distribution of sand grains from insoluble residues of (*A*) sandstone, 20 cm. from basin rim, 2–4 cm. deep; (*B*) sandstone, from basin rim, 1 cm. deep; (*C*) sand from *L. planaxis* collected from basin of Fig. 5; and (*D*) sand from beach, 20 meters distant from samples *A*, *B*, and *C*.

which varied irregularly from 7.7 per cent $CaCO_3$ near the surface to 7.2 per cent at the bottom. For comparison, beach sand 25 meters distant from the sandstone samples was found to contain only 1.6 per cent $CaCO_3$, probably all in the form of shell fragments.

The insoluble residue was of the rock sample collected from a depth of 2–4 cm. in the drill hole and of another sample from the center of a basin rim was sieved, revealing almost identical grain-size distributions, as shown in Figure 11. The median diameter of grains in both sandstone samples is 0.210, classifying them as fine sands. Both samples are poorly sorted and contain even some very coarse sand grains. Microscopic examination of the sand grains showed them to be angular in shape and composed of the minerals listed in Table 1. This analysis was made by Dr. Thomas Clements.

TABLE 1

MINERAL COMPOSITION OF INSOLUBLE RESIDUE OF SANDSTONE

	Percentage
Light minerals:	
Quartz	40
Orthoclase	45
Plagioclase (oligoclase-andesine)	10
Heavy minerals	5
Biotite—very abundant	
Chlorite—a few grains	
Hornblende—a few green grains	
Magnetite—rare grains	
Serpentine?—rare grains	

ORGANISMS OF THE BASINS

A wide and varied community of plants and animals live together in the basins. Some of them live only in the higher basins, while others occur only in low basins, where occasional splashes of water or spray prevent complete drying out during low tide. The longer exposure of the higher basins also results in a higher maximum temperature during the day, a limiting factor for marine life.[19]

There are marked changes in the number and species of algae in the basins throughout the year, with greatest abundance during winter, when the tide-pool water is coldest and the sunlight is not too strong. As illustrated in Fig-

[19] A. B. Klugh, "Factors Controlling the Biota of Tide-Pools," *Ecology*, Vol. V (1924), pp. 192–96.

ure 1, during March less than 20 per cent of the basins in the 0–12-meter zones contain attached red, brown, or green algae, in contrast to the 24–30-meter zones farther seaward, where all basins contain some algae. Counts made during August show that fewer basins in all zones contain algae. The basin illustrated in Figure 5, for example, was barren of algae in August. A collection of algae, believed to be fairly representative, was made in March and in August. The specimens were identified by Dr. E. Yale Dawson, whose list is given in Table 2, together with information on microscopic algae examined by Professor W. E. Allen. That the collection was not exhaustive is suggested by the large number of algae known to occur in the intertidal zone elsewhere near La Jolla.[20]

TABLE 2

ALGAE IN THE BASINS

RED ALGAE:	
Endocladia muricata	Very abundant in outer basins
Polysiphonia simplex	Abundant in August
Centroceras clavulatum	Occasional
Corallina gracilis f. densa	Occasional
Gelidium crinale	Occasional
Gigartina canaliculata	Occasional
Laurencia pacifica	Occasional
Lithophyllum decipiens	Occasional
Petrocelis sp.	Occasional
Rhodoglossum affine	Occasional
BROWN ALGAE:	
Ralfsia sp.	Abundant
Ectocarpus granulosus	Abundant in March
Colpomenia sinuosa	Occasional
Petrospongium gelatinosa	Occasional
GREEN ALGAE:	
Chaetomorpha californica	Abundant
Cladophora sp.	Occasional
Enteromorpha sp. (juvenile)	Occasional
Ulva californica	Occasional
BLUE-GREEN ALGAE	Abundant
DIATOMS (sedentary species)	Occasional
DINOFLAGELLATES	Occasional

Animals collected from the basins at the same time are listed in Table 3. Most of them are commonest in the 21–30-meter zones, and some occur only in those zones. A prominent exception, however, are the *Littorinas*, which were found in nearly every basin of all zones.

During the investigation it was discovered that a large number of sand grains were excreted by *Littorinas*. Examination of the intestines of these snails by Dr. W. R. Coe showed them to be jammed with sand grains and sessile blue-green algae. In order to obtain a large sample of the ingested sand, 2,600 individuals of *Littorina planaxis* were collected from the basin shown in Figure 5. These had a total weight of 87.5 gm. and probably amounted to three-fourths of all the snails living in that basin, the remainder being very small individuals. During the first 24 hours, the 2,600 snails excreted 0.311 gm. of sand, or 0.00012 gm. per snail. No additional sand was excreted during the following 24 hours. A separate collection of 104 very large specimens yielded an average of 0.0015 gm. each. After disaggregation and removal of organic matter with hydrogen peroxide, followed by 1 normal hydrochloric acid, the catch from the first group was sieved. The size distribution of the grains is shown in Figure 11. It should be noted that the shape of the histogram is very similar to those of the insoluble residues of the sandstone in which the basins are formed. The only other likely source of sand for the snails was a small beach about 25 meters distant, but Figure 11 shows that the size

[20] E. Yale Dawson, "An Annotated List of the Marine Algae and Marine Grasses of San Diego County, California," *San Diego Soc. Nat. Hist., Occas. Paper No. 7* (1945).

distribution of the beach sand is entirely different from that excreted by the snails. The median diameter of the snail sand was 0.220 mm., very close to the value of 0.210 mm. for the sandstone, in comparison with the 0.350-mm. median diameter of the beach sand. It therefore

TABLE 3

ANIMALS IN THE BASINS

MOLLUSCA:	
Littorina planaxis	Very abundant
L. scutalata	Common
Tegula funebralis	Common
Acmaea persona	Common
A. cassis pelta	Occasional
Callistochiton crassicostatus	Occasional
Lepidochitona hartwegii	Occasional
Mytilus californianus	Occasional in outer basins
ARTHROPODA:	
Copopoda	Abundant
Balanus glandula	Common
B. tintinnabulum californicus	Occasional in outer basins
Pachyrapsus crassipes	Occasional in outer basins
Amphipoda	Occasional
Isopoda	Occasional
ANNULATA:	
Polychaeta worms	Occasional
COELENTERATA:	
Cribrina xanthogrammica	Occasional in outer basins

seems likely that the sand ingested by the snails was obtained from the surface of the rock in or near the basins by means of their filelike radulas, with which they scrape detritus and microscopic plants from the rock surface.[21] In this process of collecting food, numerous grains of the rock are included. It is evident, therefore, that the snails are agents active in the erosion of the sandstone marine benches. If the weight of sand ingested by snails is about constant throughout the year, extrapolation suggests that snails living on a sandstone bench 30 meters wide and 100 meters long are capable of eroding about 500 kg. of the sandstone per year. After excretion the coarser grains are probably added to the beaches by the waves, and the finer grains are carried seaward.

[21] E. F. Ricketts and Jack Calvin, *Between Pacific Tides* (Stanford, Calif.: Stanford University Press, 1939), pp. 14, 21, 22, Pl. I.

WATER OF BASINS

ANALYSES

Early in the investigation it was believed that the composition of the water found in the basins would be a clue to their origin. Accordingly, water samples were collected at intervals during one day in November and another day in December, 1943, from twenty-one basins of all types. The water temperature varied from about 7°.5 C. in the early morning to about 24°.0 C. in the afternoon. Similarly, the average pH at 0530 hours (5:30 A.M.) was 8.12 and at 1900 hours (7:00 P.M.), 8.62. Intermediate values were found at 0900 and 1500 hours (9:00 A.M. and 3:00 P.M.). Samples collected from the ocean during this period had a pH of 8.00–8.20. For comparison, a few measurements made in August, 1945, showed afternoon temperatures of 34°.5 C.

A more complete study was made during April and May, 1944, of eight basins representative of most of the zones of Figure 1. Water samples were collected in two series, the first of which was a 28-hour period of April 27 and 28, which was interrupted at night by the renewal of water at high tide. In order to obtain data on water characteristics during a night, another series, of 12 hours length, was collected a week later, May 5 and 6,

when the tidal cycle had progressed so that night was the time of low tide instead of high tide. At 2- or 3-hour intervals in each series, water samples were obtained in two 100-ml. citrate bottles, held just at the surface so that water flowed in without bubbling. The bottles were tightly stoppered and carried in a dark cool container to the laboratory, where a pH measurement was made immediately. All samples were then stored in the dark at 5° C. while the other analyses were made. All analyses were completed within 4 days after collecting.

On the basis of the pH measurements, all samples collected from one basin were selected for more complete study, together with those from the ocean and a few from the other basins. The basin chosen (Fig. 5) has a surface area of about 0.50 square meter and a water volume of 17 liters. The results of these analyses are given in Figure 12, which also includes the tide curve (*A*) and routine measurements of solar radiation by a pyrheliometer at Scripps Institution (*B*). During the day the sun's radiation was sufficient to raise the temperature of the basin water from 13°.3 C. (*C*) in the morning to 28°.0 C. in the afternoon. The afternoon temperature of the basin water was high, in contrast to the relatively constant temperature of the nearby ocean surface: 13°.8–17°.5 C. During the night the temperature of the water in all basins investigated was from 1° to 3° higher than that of the sea and of the air. Computations show that this apparently resulted from the fact that during the day only about 80 per cent of the heat from incident radiation was used in evaporation, back radiation, and temperature increase of the water.[22] The remainder of the heat was probably transferred to the rock beneath the basin, the rock serving as a heat reservoir, which returned this heat to the water during the night.

The rise of temperature during the day resulted in evaporation of some of the sea water in the basin, so that the chloride ion, determined by titration with silver nitrate,[23] increased from 18.50 to

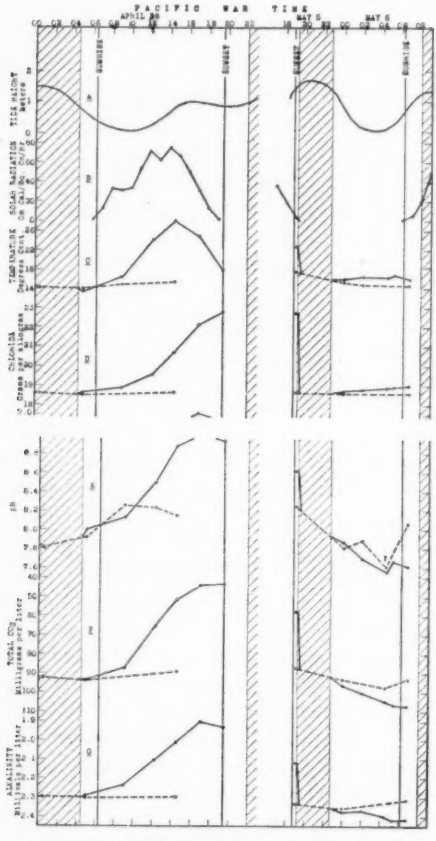

FIG. 12.—Diurnal variation of water characteristics of the basin shown in Fig. 5. Dashed line shows variation for ocean water collected near the basin. Crosshatching indicates flooding of basin at high tide.

[22] H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans* (New York: Prentice-Hall, 1942), pp. 62, 111.

[23] *Ibid.*, p. 50.

22.79 parts per thousand (Fig. 12, *D*). These values correspond respectively to salinities, or total salt contents, of 33.42 and 41.17 parts per thousand, and to specific gravities of 1.0251 and 1.0301 if there were no deposition of salt.[24] The chlorinity change indicates that about 19 per cent of the water in the basin evaporated. A smaller increase of chlorinity was found during the night series.

The pH (Fig. 12, *E*), measured by a Beckman-type meter having a glass electrode, was found to exhibit a diurnal cycle similar to that shown by the limited measurements made during winter. During the day it rose from about 7.90 at sunrise to 9.00 at 1630 hours, after which it dropped again near sunset. In the night series, the pH dropped from 7.93 at sunset to 7.56 at 0430 hours, but near sunrise it rose again before the basin water was renewed at high tide. Water collected from the ocean near by showed a similar but more moderate variation, ranging between a pH of 7.61 (?) at night to 8.26 during the day. Such a large variation of pH in sea water is probably restricted to the shallow area near the rocky shore, because numerous samples collected by E. G. Moberg[25] off a sandy beach and from the open ocean 5 and 10 miles west of La Jolla had a pH usually between 8.1 and 8.2, respectively.

Total CO_2 was determined, using a modification of the Van Slyke manometric gas apparatus.[26] It was found to vary inversely with pH; but, for ease of comparison, it is shown in Figure 12, *F*, with an inverted scale. During the day, total CO_2 decreased from about 90.00 mg. per liter at sunrise to 43.31 mg. per liter just before sunset. During the night it increased from about 92.00 mg. per liter at sunset to 107.28 mg. per liter at sunrise.

A variation parallel to that of total CO_2 was found for alkalinity, or milliequivalents of carbonic and boric acid components combined with calcium.[27] This is also known as "titratable base" and "excess base." As shown in Figure 12, *G*, alkalinity decreased from about 2.300 milliequivalents per liter at sunrise to 1.905 milliequivalents per liter at 1700 hours. At night it increased from about 2.355 milliequivalents per liter at sunset to 2.420 milliequivalents per liter just before sunrise.

In addition to the analyses shown in Figure 12, a few of the samples were tested for free ammonia, using Nestler's reagent. All tests were negative, indicating that ammonia, if present, exists in amounts less than 0.4 mg. per liter.

RELATION TO ORGANISMS

As a result of their life-processes, animals use O_2 and form CO_2. In aquaria the CO_2 given off by fish and invertebrates gradually accumulates, forming carbonic acid and causing a lowered pH.[28] Plants in their respiration also convert O_2 to CO_2, but this is overbalanced during the daytime by the reverse process of photosynthesis, in which CO_2 and H_2O are converted into carbohydrates, which are stored, and O_2, which is set

[24] Martin Knudsen, *Hydrographical Tables* (Copenhagen: G. E. C. Gad, 1901), pp. 18, 22, 41, 42.

[25] "The Hydrogen Ion Concentration of Seawater off the Coast of Southern California," *Proc. 3d Pan-Pacific Sci. Cong., Tokyo* (1926), pp. 221–29.

[26] D. M. Greenberg, E. G. Moberg, and E. C. Allen, "Determination of Carbon Dioxide and Titratable Base in Sea Water," *Indust. Eng. Chem., Anal. Ed.*, Vol. IV (1932), pp. 309–13.

[27] *Ibid.*

[28] E. M. Brown, "Notes on the Hydrogen Ion Concentration, Excess Base, and Carbon-Dioxide Pressure of Marine Aquarium Waters," *Proc. Zoöl. Soc.*, Part 4 (1929), pp. 601–13.

free.[29] During the night, therefore, plants can be expected to increase the CO_2 content of the water in the tide pools by respiration, as do the animals; but in the daytime, to reduce it by photosynthesis. This is reflected in a low pH during the night and a high pH during the day. F. W. Gail,[30] for example, found that the pH of tide pools in Puget Sound varied between 7.43 just before sunrise and 8.80 in the afternoon. E. B. Powers[31] found nearly as great variation in a small lagoon in Puget Sound. Larger bodies of water, such as bays, show the same type of variation in pH; but, because of the large volume of water, compared to volume of organisms, the fluctuation is less extreme. E. G. Moberg[32] found that the pH of water in Mission Bay, near San Diego, changed from 7.87 at night to 8.13 during the day. Similarly, J. R. Bruce[33] found the pH of water in Port Erin Bay highest at near-shore stations and during the summer months, when photosynthetic activity was greatest; but he reported only results obtained from measurements made during the daytime. The greatest extremes in pH of water from bays seem to be encountered during ebb tides, when the water is drained from extensive areas covered by plants and animals.

As a check of the ability of the predominant tide-pool animal, *L. planaxis*, to produce a lowered pH, about twenty of the snails were placed in each of two dishes, each containing about 200 cc. of unfiltered sea water and a few chips of rock from a tide-pool wall. The rock chips had a thin coating of microscopic algae. Two other dishes contained only the sea water. One dish with snails and rock chips and one with sea water alone were placed in a dark constant-temperature room set at 15° C., while the other pair was put in sunlight during the day and removed to the dark room at night. Measurements of pH in all dishes were made with the aid of Mr. Gregory Jankowsky at 0900 and 1600 hours on several successive days. As shown in Table 4, the pH of dishes kept always in the dark showed a nearly regular decrease from the original value of 8.38. At the end of the period the pH of the dish containing water, snails, and rock chips had decreased to 7.68, while that for the dish containing only water was 8.00, the difference probably being due to the greater amount of CO_2 given off by the snails compared to that given off by microscopic plants in the dish which contained no snails. Of the other pair of dishes, the one containing only water also showed a regular decrease of pH, presumably again because the microscopic life present was insufficient to give off much CO_2 at night or to use much during the day. The other dish, however, showed an interesting variation of pH between about 8.2 in the afternoon and 7.7 at night, clearly indicating that during the night the snails gave off a considerable amount of CO_2 but that during the daytime the plants

[29] M. C. Sargent and J. C. Hindman, "The Ratio of Carbon Dioxide Consumption to Oxygen Evolution in Sea Water in the Light," *Jour. Marine Res.*, Vol. V (1943), pp. 131–35; S. M. Marshall and A. P. Orr, "The Photosynthesis of Diatom Cultures in the Sea," *Jour. Marine Biol. Assoc.*, Vol. XV (1928), pp. 321–60.

[30] "Hydrogen Ion Concentration and Other Factors Affecting the Distribution of Fucus," *Puget Sound Marine Sta. Pub.*, Vol. II (1920), pp. 287–305.

[31] "The Variation of the Condition of Sea-Water, Especially the Hydrogen Ion Concentration, and Its Relation to Marine Organisms," *Puget Sound Marine Sta. Pub.*, Vol. II (1920), pp. 369–85.

[32] "Effect of Tidal Changes on Physical and Chemical Conditions of Sea Water in the San Diego Region," *Bull. Scripps Inst. Oceanog.*, Vol. I (1927), pp. 1–14. Note that the published values were later found to be 0.27 too high.

[33] "Seasonal and Tidal pH Variations in the Water of Port Erin Bay," *38th Ann. Rept. Oceanog. Dept. Univ. Liverpool* (1924), pp. 35–39.

were able to utilize all the CO_2 given off. The afternoon pH of this dish was higher than the one containing only sea water because there was somewhat more abundant plant life on the rock chips than in the water.

A diurnal cycle of pH was also found in all the tide pools examined. This is well illustrated by Figure 12, *E*, which shows that pH rose to 9.00 in the afternoon and decreased to 7.56 just before sunrise, in contrast to the normal variation in the open sea of between 8.0 and 8.2. This resulted from the diurnal variation of CO_2 in the tide pools (Fig. 12, *F*) between 43.3 mg. per liter in the afternoon and 107.3 mg. per liter just before sunrise. By using the equations and tables summarized by Sverdrup, Johnson, and Fleming,[34] at the existing temperature, chlorinity, and $[H_2CO_3]$, the partial pressure of CO_2 in the basin at night was found to be 1.60 Torr, in contrast to the usual partial pressure of CO_2 in air of about 0.23 Torr. Thus, at night the plants and animals may have liberated more CO_2 in respiration than the water analyses indicate, the remainder having escaped into the air. On the other hand, during the day the partial pressure of CO_2 in the basin water was only 0.012 Torr, well below the partial pressure in air, 0.23 Torr. Accordingly, during the day additional CO_2 may have dissolved in the water from the air, so that the algae may have used more CO_2 in photosynthesis than the analyses indicate. The fact that the water surface was not stirred or rippled by the wind suggests that the difference may not be great, however.

TABLE 4

LABORATORY TEST OF THE EFFECT OF ORGANISMS ON pH OF SEA WATER

DISH	TREATMENT	pH						
		Nov. 30 1600	Dec. 1		Dec. 2		Dec. 3	
			0900	1600	0900	1600	0900	1600
Water, snails, and rock chips	Dark, night and day	8.38	7.90	7.70	7.75	7.70	7.70	7.68
Water only	Dark, night and day	8.38	8.25	8.05	8.10	8.00	8.00	8.00
Water, snails, and rock chips	Dark at night, sun in day	8.38	7.90	8.15	7.70	8.18	7.70	8.10
Water only	Dark at night, sun in day	8.38	8.28	8.10	8.10	8.00	8.03	8.03

SOLUBILITY OF CALCIUM CARBONATE

The most direct method of determining whether $CaCO_3$ is precipitated or dissolved by the water in the basins would be to measure the change of calcium ion in water samples collected at intervals during the day and night. The total salts of sea water constitute about 3.5 gm. per liter, and only about 1.2 per cent of this is calcium. Moreover, only about 11 per cent of the calcium is combined as carbonate and bicarbonate. Changes in calcium content related to changes in carbonate and bicarbonate of the water must, therefore, be minute and probably smaller than the error of the gravimetric analysis of calcium.

Another method of attacking the problem is through investigation of the variation of the anions with which calcium could be combined. About 89 per cent of

[34] *Op. cit.*, pp. 191, 201, 202.

the calcium can be assigned to chloride and sulphate; and most of the rest is combined with carbonate, bicarbonate, or borate ions. Since $CaSO_4$ and $CaCl_2$ are much more soluble and are less affected by temperature and other factors, they will remain in solution until after much of the $CaCO_3$ is precipitated. Moreover, for lack of a source of more chloride and sulphate ions, new calcium is not likely to be dissolved from the rock and combined as $CaSO_4$ or $CaCl_2$. Biochemical activities, however, do constitute a source of extra CO_2, which may be added as H_2CO_3 to the $CaCO_3$ of the rock to form the more soluble $Ca(HCO_3)_2$. The biochemical processes may also deplete the CO_2 content of the water, tending toward the reverse condition of deposition of $CaCO_3$ under certain conditions. The fact that there exists a means by which the solubility of $CaCO_3$ can vary, that the water is nearly saturated with $CaCO_3$, and that $CaCO_3$ is the first form in which calcium may be deposited during evaporation indicates that study of the variation of carbonic acid components may aid in solving the problem of the origin of the tide pools. The problem of the solubility of $CaCO_3$ in ocean water has been of interest for many years because of its dependence on biological activities and because of relationships with abundant marine sediments high in $CaCO_3$, contributed partly as shell and skeletal debris but also as true precipitates; therefore, the basic constants and equations have been determined fairly accurately.

The first step is the calculation of the amount of carbonate, bicarbonate, carbonic acid, and borate ions present in each water sample collected from the basin. The basic data for the computations are given in Figure 12. The necessary equations are derived and explained by Sverdrup, Johnson, and Fleming[35] in a concise summary of the scattered reports of studies made by K. Buch, R. H. Fleming, H. W. Harvey, E. G. Moberg, Roger Revelle, H. Wattenberg, and others. A slight modification of the four basic equations was used,[36] as follows:

$$[HCO_3^-] = \frac{[\Sigma CO_2]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1},$$

$$[CO_3^=] = \frac{[\Sigma CO_2]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1} \times \frac{K_2'}{[H^+]}$$

$$[H_2CO_3] = \frac{[\Sigma CO_3]}{\frac{[H^+]}{K_1'} + \frac{K_2'}{[H^+]} + 1} \times \frac{[H^+]}{K_1'},$$

$$[H_2BO_3^-] = \frac{K_B' \times [\Sigma H_3BO_3]}{[H^+] + K_B'} - [H^+] + \frac{K_W}{[H^+]}.$$

The first and second dissociation constants for carbonic acid needed to solve

[35] *Op. cit.*, pp. 195–202.

[36] Abbreviations and symbols are:

[ ] = gram-atoms per liter
$[A]$ = total alkalinity = $[HCO_3^-] + 2[CO_3^=] + [H_2BO_3^-]$
$[A_{CO_2}]$ = alkalinity due to carbonic acid components = $[HCO_3^-] + 2[CO_3^=]$
$[H^+]$ = hydrogen-ion concentration = 10^{-pH}
K_1' = first dissociation constant for carbonic acid = $10^{-pK_1'}$
K_2' = second dissociation constant for carbonic acid = $10^{-pK_2'}$
K_W = ion-product constant for water = 10^{-pK_W}
K_B' = apparent first dissociation constant for boric acid = $10^{-pK_B'}$
Cl = chlorinity = chlorine in grams per kilogram of water, o/oo
Chlorosity = chlorinity expressed as grams per 20° C. liter of water
T = temperature in degrees centigrade

these equations can be computed from the following:

$$pK_1' = 6.47 - 0.188\sqrt[3]{Cl} + 0.006\,(20.0 - T)\,,$$

$$pK_2' = 10.288 - 0.443\sqrt[3]{Cl} - 0.0046\,Cl + 0.011\,(20.0 - T)\,.$$

The apparent first dissociation constant of boric acid and the ion-product constant for water can be expressed as

$$pK_B' = 9.22 - 0.123\sqrt[3]{Cl} - 0.0086\,Cl\,,$$

$$pK_W = 14.170 - 0.1517\sqrt[3]{Cl} + 0.0083\,Cl + 0.035\,(20.0 - T)\,.$$

Lastly, the total concentration of boric acid is

$$[\Sigma H_3BO_3] = 0.0000221 \times \text{chlorosity}\,.$$

Substituting the values for the dissociation constants and the total boric acid in the four basic equations and using the measured values of $[\Sigma CO_2]$ and pH, the concentrations of $[HCO_3^-]$, $[CO_3^{=}]$, $[H_2CO_3]$, and $[H_2BO_3^-]$ were computed for each sample collected from the basin. A partial check of the computations was made using the relationship

$$[\Sigma CO_2] = [HCO_3^-] + [CO_3^{=}] + [H_2CO_3]\,.$$

It should be noted that nowhere has alkalinity, $[A]$, been used; and since

$$[A] = [HCO_3^-] + 2[CO_3^{=}] + [H_2BO_3^-]\,,$$

this offers a method of checking both the analyses of the water samples and the computations based on them. It was found, using this equation, that the computed and measured alkalinities of the twenty-two samples studied agreed within 6 per cent in all cases and averaged 2 per cent. In order to base subsequent computations of calcium on the measured $[A]$, as well as on the measured pH and $[\Sigma CO_2]$, the final alkalinity was taken as the average of the measured and the computed values, and $[HCO_3^-]$, $[CO_3^{=}]$, and $[H_2BO_3^-]$ were adjusted in the same proportions as computed.

The concentrations of the anions combined with calcium having been determined, the concentration of Ca^{++} in milligrams per liter was computed, with the results shown in Figure 13. From this

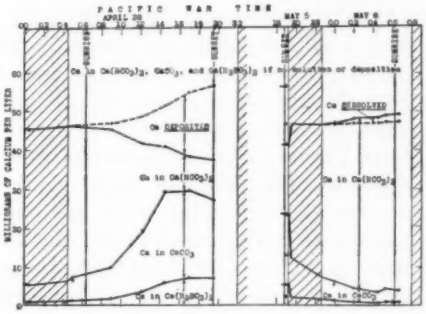

FIG. 13.—Diurnal variation in concentration of calcium combined with carbonate, bicarbonate, and borate ions in the water of the basin of Fig. 5. The dashed line indicates the concentration of this calcium if no solution or deposition occurred. Cross-hatching indicates flooding of basin at high tide.

diagram it appears that during the daytime, when $[\Sigma CO_2]$ is lowest, the calcium is combined chiefly as $CaCO_3$. For the conditions prevailing in the afternoon, only about one-fourth of the calcium is combined as $Ca(HCO_3)_2$; and, because of the high pH at that time, there is a nearly equal amount of calcium in $Ca(H_2BO_3)_2$. During the nighttime, the situation is very different, for then, when $[\Sigma CO_2]$ is highest, nearly all the calcium exists as $Ca(HCO_3)_2$, and only small quantities of $CaCO_3$ and $Ca(H_2BO_3)_2$ are present. It should be noted from Figure 13 that the solid line forming the top boundary of Ca^{++} in $Ca(HCO_3)_2$ also

represents the total concentration in the water of calcium combined with all carbonic and boric acid components.

In order to determine whether calcium is deposited from the water or dissolved from the rock, it is necessary to compute the concentration of calcium *available* for distribution between carbonate, bicarbonate, and borate anions. As the tide receded after having flooded the basins, it left them filled with water of normal chlorinity. After the pool was exposed for a time during low tide, evaporation proceeded, with resulting concentration of the salts in the water. If no deposition of salts occurred, the chlorinity serves as an index of the increased concentration because the water is undersaturated with chlorides. Therefore, by adjusting the concentration of calcium at the time the basin was first exposed above the retreating tide by an amount proportional to the increase of chlorinity, the total concentration of calcium in the water available at a later time for combination with carbonic and boric acid components may be determined. The diurnal variation of this quantity is shown by the dashed line of Figure 13.

Decision as to whether deposition or solution of $CaCO_3$ occurs can readily be made from the relationships of Figure 13 by comparing the concentration of calcium available in the water with the concentration of calcium actually combined with the carbonic and boric acid components. In the afternoon there was available more calcium, which must be combined with carbonic or boric acid components, than the conditions of high *p*H and high temperature permitted the water to retain. The excess was precipitated. In this series of measurements the amount deposited was about one-third of the total, or 20 mg. per liter of water. During the night the reverse was true, for, while the concentration of calcium originally available in the water increased slightly because of evaporation, the amount actually present showed a greater increase. The additional calcium presumably was dissolved from the rock basin.

One or two other factors should also be considered. The estimate of available calcium was based on the assumption that no Cl^- had been deposited; however, if some NaCl crystallized at the edge of the basin the amount of evaporation, as indicated by chlorinity of the water, would be too low. As a result, even more calcium may have been available during the daytime than is indicated, with resulting greater precipitation of $CaCO_3$. No salt was noted, however, on the day that the water samples were collected. This correction could not have applied to the night series because of the lower temperature and the fact that the chlorinity increased only very slightly. Another circumstance may have caused an apparently too-high concentration of calcium in solution during the day series. If the reactions leading to precipitation were sluggish, so that the water became supersaturated, or even if the precipitation did occur but in colloidal form, Figure 13 would still show the concentration of calcium present in the water but, given sufficient time with no further change of conditions, even more calcium would probably be deposited. That such conditions actually exist is shown by the fact that the ion-product of $[Ca^{++}] \times [CO_3^{=}]$ in the afternoon reached $6.35(10)^{-6}$. According to the most recent data,[37] the saturation value, or the solubility-product constant, when corrected by the usual factors for the

[37] J. C. Hindman, "Calcium Equilibria in Sea Water," Ph.D. thesis (Scripps Inst. Oceanog., 1942), p. 39.

prevailing temperature and chlorinity,[38] is about $0.90(10)^{-6}$. Thus, even though Figure 13 shows that some $CaCO_3$ had been deposited, the water was still seven fold supersaturated. During the night, on the other hand, the ion-product of $[Ca^{++}] \times [CO_3^{=}]$ reached a low value of $0.72(10)^{-6}$. For that temperature and chlorinity the solubility-product constant is about $1.14(10)^{-6}$, indicating that, although some new Ca^{++} has been obtained by solution of the rock cement, the water was only about 60 per cent saturated. Similar computations show that the sea water at the time it flooded the basins was almost exactly saturated, having an ion-product of about $1.10(10)^{-6}$.

CONCLUSIONS

ORIGIN OF BASINS

Although this type of rock tide pool has been described by a number of writers, few have offered theories as to origin. In one of the earliest reports, Henkel[39] suggested that similar basins at Vancouver Island are due largely to pothole abrasion, but this origin is belied by the fact that her photographs show the basins to be shallow and broad, in contrast to the deep narrow pothole usually encountered. Moreover, at La Jolla the walls are fluted and have soft friable surfaces. Seldom may an abrasive rock tool be found within a basin.

Kuenen[40] ascribed basins found on Morotai and Wotop islands to deposition of sea salt through evaporation at the edge of a pool of water, thus indurating a circle of rock which was left as a raised rim by the faster abrasion of the less resistant rock inside and outside the pool. At La Jolla it was commonly observed that the visible salt incrusting the rim is dissolved by the first wave which floods over the basin. Moreover, many of the basins have no rim and therefore could not have had that origin. Kuenen also supposed that the basins are restricted to tropical areas, though they had been reported from Vancouver Island, Canada.

In a recent paper Wentworth[41] ascribed certain basins in Hawaii to solution, not by sea water, which is ordinarily saturated with $CaCO_3$, but by fresh water from rain or run-off. This explanation suffers serious drawbacks in southern California.

As a result of the rock and water analyses already discussed, the writer offers the following sequence of events in the basin formation. When a ledge of calcareous rock, or sandstone cemented by calcite, is covered by the waves or by spray at high tide but is partly dried off at low tide, small pools of water remain in initial depressions of the rock, such as joints, ripple marks, concretionary areas, etc. Various intertidal plants and animals become established. Although the sea water is about saturated with calcium when it first covers the ledge, various changes in water characteristics take place as a result of biological processes of the plants and animals. During the daytime, the plants use CO_2 in photosynthesis, thereby raising the pH and reducing the total CO_2 content of the water to the point where it can little more than balance the calcium as $CaCO_3$. As a result of the high temperature, high pH, and low CO_2 content, much of the $CaCO_3$ is precipitated. If evaporation continues, all the other salts may be deposited; but this rarely occurs except in the smallest

[38] Sverdrup, Johnson, and Fleming, *op. cit.*, pp. 206–7.

[39] *Op. cit.*

[40] *Op. cit.*

[41] *Op. cit.*

basins. The $CaCO_3$ deposited from the main part of the tide pool is only loosely attached to the rock bottom, and it is washed out by turbulent waves at the next high tide. If the rock surface between the pools dries out at low tide, much of the $CaCO_3$ is deposited on the capillary fringe of the pool, where it serves as an additional cement for the rock, thus strengthening the rim area so that abrasion and weathering proceed less rapidly than in the surrounding area, and a raised rim is eventually left by erosion of the less resistant surrounding rock.

FIG. 14.—Karstlike topography developed by continued formation of solution basins (January, 1944).

During the night a different process is dominant. In the absence of light the plants no longer use CO_2 in photosynthesis but instead give off CO_2 in respiration, as do the animals. The resulting increase of CO_2 above the normal content for sea water lowers the pH. The low temperature, low pH, and high CO_2 content cause the calcium of the water to be combined with bicarbonate ion. In this state, the water is unsaturated with calcium, so that some of the $CaCO_3$ of the rock cement is converted to $Ca(HCO_3)_2$ which dissolves in the water. Once the cement between the sand grains is removed, the grains themselves are easily loosened and carried away by the waves. Many of the sand grains are ingested by snails, which therefore constitute an agent of erosion. Since the animals are the chief donors of CO_2, solution is greatest where they are most abundant and a cavity in the basin wall results. As the basin deepens the cavities become elongate, forming the flutings, within which clusters of snails may be seen.

As time goes on, the basin becomes wider and deeper, until finally it coalesces with other basins or reaches a rock joint. In either case the water-level may be lowered, and sometimes the basin may be almost completely drained. Thereupon another, a second-generation basin, may form in the bottom of the first basin. Eventually, the continued formation of solution basins may result in considerable weathering of the coastal rocks. Locally, it may even be the dominant process causing retreat of the coast (Fig. 14).

A similar process may be instrumental in the formation of some kinds of stone-lace (Fig. 15), for many small cavities in ledges or boulders are filled with snails and contain a small amount of water found to have a low pH. Stone-lace and solution basins on the top and upper sides of boulders near the Scripps Institution of Oceanography are sharp and well defined, but on the bottoms the basins are few, are weathered, and are partly obliterated. This probably indicates a change in the position of some boulders, probably resulting from exceptionally severe storm waves.

It is of interest to know whether basin-forming processes have an annual, as well as a diurnal, cycle. Most of the water analyses were made in April and May; but limited data collected in November, December, and August indicate that deposition during the day and solution during the night characterize all seasons at La Jolla. While plants are less abundant

in the pools during the summer, deposition continues because of the greater amount of evaporation. It is possible that solution is somewhat more rapid during the winter, when plants and animals are more abundant, with resulting greater contribution of CO_2 by respiration at night.

The general scarcity of these features around the coast of the United States is understandable when the character of the coast is considered. In New England the coast consists of noncalcareous igneous and metamorphic rocks. Most of the rest of the coast bordering the Atlantic Ocean and the Gulf of Mexico is sand beach. The main exception is in the vicinity of Key West, where there are coral reefs and where limited observations by the author showed the presence of a few solution basins. Rocks of the coast bordering the Pacific Ocean consist largely of volcanics; but locally there are outcrops of calcareous sandstones and, at least in La Jolla, the sandstone contains numerous solution basins. Wider distribution elsewhere is shown by the fact that basins have been reported in the literature, or the writer has seen them, at Bermuda, Puerto Rico, Cedros Island in Mexico, Vancouver Island in Canada, the Hawaiian Islands, Morotai Island, Wotop Island, and Ulithi Atoll.

RATE OF FORMATION

Though estimates of the rate of formation of the basins must be based on several assumptions and are therefore subject to considerable error, it is believed that estimates of the correct order of magnitude can be made, which may be of some interest. If the rate of solution of the rock is constant and is correctly indicated in Figure 13 as 0.0020 gm. of Ca^{++} per liter per night, then during an entire year 0.0025 gm. of Ca^{++}, or 0.0062 gm. of $CaCO_3$, is removed per square centimeter of the basin area. Since the rock contains about 8 per cent $CaCO_3$, the total amount of rock dissolved or uncemented is 0.075 gm. per square centimeter per year. The uncemented rock grains are removed by waves and by the snails feeding on blue-green algae. A single measurement of the quantity of rock excreted in one day by the snails from the basins was 0.311 gm., or 0.000062 gm. per square centimeter of the basin. This quantity is 0.022 gm. per year, about one-third the amount dissolved and uncemented, the remainder presumably being removed by wave action.

FIG. 15.—Stone-lace in a boulder near the Scripps Institution of Oceanography. There is a cluster of snails in each of the small cavities (January, 1944).

The removal of rock at the rate of 0.075 gm. per square centimeter per year corresponds to a deepening of about 0.030 cm. per year. Therefore, at the present stage of development of the basin, about 33 years would be required to deepen it 1 cm. Since the average depth below the top of the rim is 5 cm., the time required to develop the basin would have been of the order of 165 years. In the early stages the basin probably deepened more slowly, so that its total age probably exceeds 200 years. In many of the areas studied, some basins are deeper

than 25 cm., and there are numerous indications of previous generations of basins. It is, therefore, impossible to estimate the date when basin formation in these areas first began.

That an age of 200 years is not unduly great is shown by a comparison of some of the basins with photographs taken about 40 years ago. The changes are relatively insignificant and may have been caused by people walking on the basins.

ACKNOWLEDGMENTS.—Grateful acknowledgment is due many members of the staff of the Scripps Institution of Oceanography for their interest and help: Dr. E. G. Moberg, who made available chemical equipment for water analyses; Dr. C. E. ZoBell and Mr. Gregory Jankowsky, who furnished a pH meter and also made some measurements themselves; Dr. W. R. Coe, who examined the intestinal content of snails collected from the pools; Professor W. E. Allen, who examined the plankton in water from the pools; and Dr. Denis L. Fox and others, who made many helpful suggestions. It is also a pleasure to acknowledge the assistance given by Dr. R. H. Fleming, who helped interpret the chemical analyses; Dr. E. Yale Dawson, who identified the algae collected from the pools; and Mr. Edwin Bushman, who assisted in the early part of the geological investigation.

MIOCENE SUBMARINE DISTURBANCES OF STRATA IN NORTHERN ITALY

C. BEETS
Curator of the Teyler Foundation Museum, Haarlem, Holland

ABSTRACT

In the Apennines, near Florence, our colleague, J. W. R. Brueren, observed remarkable intraformational structures in Miocene strata, one of which was described in 1941. In the present paper an attempt is made to give another explanation and a more detailed description of this example. The structures originated from flowage of an unconsolidated sand layer at the top of a series of marly and sandy deposits, causing deformation of underlying strata. Differential burden due to initial concentration of sand in lenses was responsible. In the literature, only two comparable examples were to be found.

In the Turin Hills, which must be considered as the northwestern end of the Apennines, we discovered another instance of disturbed stratification. In this case the folding resulted from a sliding of rather consolidated strata in the frontal region of a delta, the development of which may be advantageously studied in the region investigated.

A few notes on other kinds of disturbed stratification in the Turin Tertiary are added. The author made an attempt to compile all available data concerning sliding and flowing structures; but, since the results are rather unsatisfactory, he refers here only briefly to the many cases described in the literature.

INTRODUCTION

In 1937 the author started detailed geological investigation of the Tertiary hills east of Turin in northwestern Italy (Piemonte) which are famous for their enormous yield of fossil material and their peculiar structure, showing three main directions of folding. An unusual example of subaqueous sliding was discovered and is here described. At the same time our colleague, J. W. R. Brueren, made observations on disturbances in Miocene strata in another, tectonically very important, part of the Apennines near Florence.[1] Both examples, mentioned briefly in our papers of 1941,[2] are now discussed more amply. Literature on sliding structures, only recently available to the writer, has aided in the interpretation of these forms. Though the last decenniums especially have yielded many observations on subaqueous disturbances of strata, we still lack sufficient data on recent examples, so the actuality principle, which must be handled very carefully, cannot be invoked to support our conclusion.[3] The deposits of recent types of geosynclinal basins cannot be studied *in situ*, which, of course, would be of the greatest value in the interpretation of strata. We must also bear in mind the possibility of convergence, i.e., identical final products may result from various causes, and the same cause may lead to different products.[4]

[1] *De geologie van een deel der Etruskische Apennijnen tusschen Firenze en Bologna* (University of Leyden thesis) (Assen: Van Gorkum Co., 1941).

[2] C. Beets, *De geologie van het westelijk deel van het Heuvelland van Monferrato tusschen Turijn en Murisengo* (University of Leyden thesis) (Assen: Van Gorkum Co., 1941); "Die Geologie des westlichen Teiles der Berge von Monferrato zwischen Turin und Murisengo," *Leidsche Geol. Meded.*, Vol. XII (1941), pp. 195–250 (an extensive summary of the foregoing paper).

[3] E. Kayser, "Der Grundsatz des Aktualismus in der Geologie," *Zeitschr. d. D. Geol. Ges.*, Vol. LXXXIII (1931), pp. 389–407; K. Andree, "Rezente und fossile Sedimente," *Geol. Rundschau*, Vol. XXIX (1938), pp. 147–67; *idem.*, "Die wichtigsten Faktoren der marinen Sedimentbildung jetzt und einst," *Geol. Archiv.*, Vol. II (1923), vi (a hardly attainable, nearly uncited, paper).

[4] Kayser, p. 405 of ftn. 3.

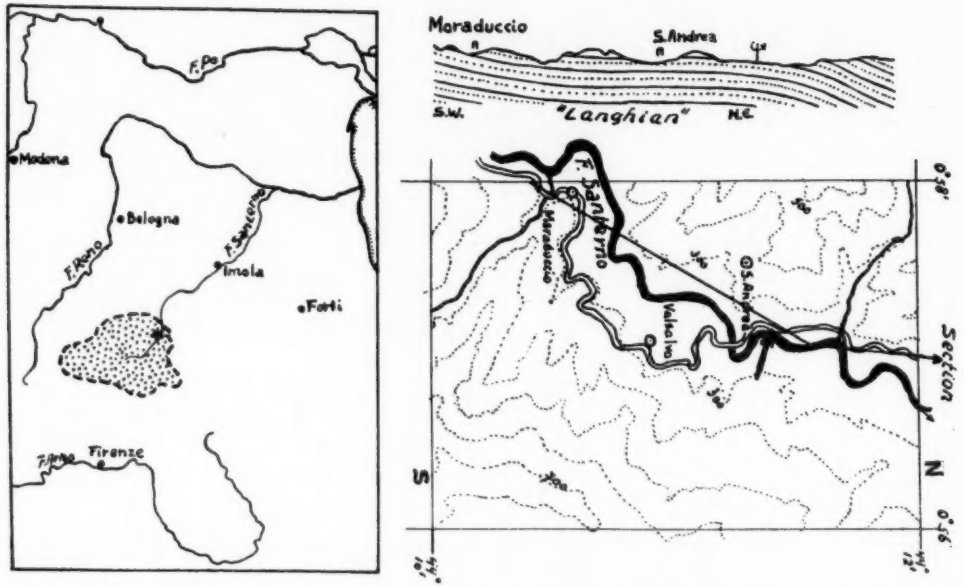

FIG. 1.—The small-scale map (about 1:2,600,000) on the left indicates the area studied by Brueren; the asterisk, the location of the photograph of Fig. 2. Map and section on the right represent Part M.6 of Brueren's geologic map and part of his Section VII, respectively (scale about 1:64,000). The map shows a "Langhian" landscape. The photograph of Fig. 2 was made near San Andrea, on the left bank of the Santerno River (arrow indicates locality and direction of view).

In the following pages the examples described in the literature are discussed very briefly.

SUBMARINE FLOWAGE IN "LANGHIAN" STRATA, NORTHEAST OF FLORENCE

In the area studied by Brueren[5] in the Etruscan Apennines (left part of Fig. 1), he discovered many examples of disturbances of "Langhian" (Burdigalian) and Helvetian strata. A fine example is given in our Figure 2, representing Brueren's Figure 2 facing page 65 of his paper. The photograph was made by G. G. Wissema, who kindly communicated some details. To him and to Brueren we express our indebtedness.

FIG. 2.—Showing result of subaqueous movement in "Langhian" strata near San Andrea (cf. Fig. 1). The breadth of the whole disturbed part of the exposed section does not exceed 16 meters, about twice the length covered by the photograph. (Photograph by G. G. Wissema.)

Brueren published the following explanation, here translated and edited with our comments (in brackets):

> In an undisturbed series of sandstones and marls, we observe two irregularly limited sandstone layers separated by an undulating marl layer. The lower sand layer is divided into pieces showing undisturbed [?] surface of contact with underlying marl, but its upper surface is undulated. The upper sandstone has a flat top surface, but now its lower surface is undulated in all directions. The deepest parts of the upper layer correspond with those places where portions of the lower sand layer have disappeared [or were thinned out].
>
> The marl between the sands has functioned as a sliding [lubricating] layer. During the sliding action the lower sand layer was partly involved. On the places where we now observe sand tumors, the sediment was accumulated. The marl layer was folded [flowed] over the sand waves, forming depressions between them. We observe a lens-shaped portion of the lower sandstone lying in a marly matrix, found back above the lower sand lens in the right part of the photo.
>
> In the depressions of the marl, sand masses of the upper layer accumulated. At the left we observe the marl mud having made its way through a sand lens, causing the irregular sand accumulation [in our opinion, it is a normally shaped portion of the whole sand lens] at the right of the intrusion. This accumulation and the big lens about in the middle of the photo [according to Wissema, the breadth of this lens is 2.40 meters] are joined by a slightly waved but rather regular sand layer showing a slight variation of thickness. Although this layer was somewhat thicker in its original state, it may give us an idea of the situation before the sliding action.[6]

It is clear that the disturbed sandy and marly deposits must have remained nearly unconsolidated until the beginning of the movement, which must be

[5] See ftn. 1.

[6] P. 59 of ftn. 1.

called a "flowage of quicksand" rather than a "sliding action."

Brueren has described both the Langhian and the Helvetian strata in this area as chiefly fine-grained, chalky sandstone layers, alternating with marly sediments, probably representing shelf deposits. In the Langhian series we may now and then observe big limestone blocks, which are only known from the near-by "Argille scagliose."[7] These peculiar formations play the same part in the tectonic history of the Apennines as the salt series in dome structures and allied phenomena. In the northwestern part of the area studied by Brueren the "Argille scagliose" and Eocene strata formed a land area which supplied the enormous amount of clastics of the Miocene series, including limestone blocks from the "Argille scagliose" formation. In the northern part of the area, quiet sedimentation took place.

It is therefore obvious that the flowing and, in general, the lateral movements near San Andrea occurred on the eastern submarine slope of the land area mentioned above.

Disturbances of this type are not common, according to the literature. Flowing of sandy deposits containing gastropods may produce interesting results, according to Krejci-Graf.[8] Flow structures, such as those described by Hadding,[9] are not comparable with Brueren's example, and it is difficult to say whether the flowage near San Andrea was quick or slow. Subaerial flowage, discussed by Kieslinger,[10] also results in different structures.

At San Andrea the sand masses do not show any stratification, and no cleavage is developed—thus indicating, presumably, an unconsolidated mass during the movements. Accordingly, we may conclude that the original stratification has been totally obliterated. We therefore use the term "flowage" instead of "sliding," in accordance with Richter's use of the term.[11]

Lippert, who has divided the sliding phenomena according to mode of movement and result, has also discussed examples of "downward movements accompanied by change of structure" (*Gekreich und Gefliess*), combined with "movements without change of structure" (*Rutschung und Gleitung*) (cf., e.g., Lippert's Figs. 2 and 3). His Figure 2, at first sight, greatly resembles Brueren's figure, but Lippert explains the structure by the slackening of speed of a gliding mass of rather consolidated tuffs and clays, accompanied by intrusion of mud —which had served as a lubricant—into the fold and fault structures developed. In our case the circumstances were different from those assumed by Lippert, and we, therefore, shall try to explain anew the structure described by Brueren.

As pointed out above, both the sandy layers and the intermediate marl must have been practically unconsolidated at the beginning of the downward movement. They were in the state of a semiliquid mass. By an unknown accident this mass flowed over undisturbed strata,

[7] *Ibid.*, pp. 58, 198.

[8] K. Krejci-Graf, "Senkrechte Regelung von Schneckengehäusen," *Senckenbergiana*, Vol. XIV (1932), pp. 295–99.

[9] A. Hadding, "On Subaqueous Slides," *Geol. For. Stockholm Forh.*, Vol. LIII (1931), pp. 377–93.

[10] A. Kieslinger, "Eine boden-physikalische Betrachtung der Gefliess-Marken (Fliesswülste)," *Senckenbergiana*, Vol. XIX (1937), pp. 127–38.

[11] H. Lippert, "Gleit-Faltung in subaquatischem und subaerischem Gestein," *Senckenbergiana*, Vol. XIX (1937), pp. 355–75 (p. 357: "Gefliess").

of which only the upper layers were slightly involved and folded (left and right parts of Fig. 2). Apparently the uppermost quicksand layer began to move differentially upon the marly mud. The development of a waved surface of contact below the drift sand resulted through the operation of the well-known principle of Helmholz (1888): A sinuous surface of contact will arise between moving fluids—in this case suspensions—of different specific weight. This action was promoted by the specifically heaviest layer lying at the top of the series.

Sand accumulated in the regularly developing wave depressions. This increased their burden in contrast to the "anticlinal" waves, where no sand could accumulate because the sand suspension flowed down their flanks into the depressions. In consequence of the growing sand accumulations, the intermediate mud and the lower sand layer (especially the latter) were pressed aside below the added overburden and were concentrated at places of least pressure. This process continued until movement stopped.

The lower sand layer was slightly consolidated, as may be proved by the sand lens at the right in Figure 2. This is a portion of the lower sand layer, which was enclosed by the intermediate mud and moved to the nearest place of least burden, where another part of the sand layer was deposited in the second lens. It must be borne in mind that the superposed lens might have originated from a marly intrusion, separating one larger lens into two portions.

The superposed undisturbed strata must have been absent at the time of flowage, as is proved by the marly intrusion on the sand lens at the left. The mud even extruded; but, as there is no trace of disturbed stratification above, the extruded mud must have been washed by the sea. It is, of course, a rather mysterious intrusion, for we should expect it at a place of low pressure, between the sand lenses of the upper layer. Most probably, however, rupture was caused by the sinking of the heavy sand lens to the bottom of the mud. This reminds us of the basic intrusions of "pietre verde" in bottom strata of several geosynclines. Note the beginning of the intrusion outside the center of the sand accumulation and its radial direction. Further, it is notable that the different mediums, sand and clay suspensions, did not undergo striking mixture during the flowage.

Lippert[12] has pointed to the existence of a so-called "whirl-zone" (*Aufwirbelungszone*) in examples of subaqueous sliding, and perhaps the structures near San Andrea also developed a whirl-zone above, for the contact between the upper sand layer and the superposed marls seems to be less sharp than the boundary between sand and the intermediate marl layer (cf. right part of Fig. 2).

It is not easy to determine the cause of the flowage of the uppermost drift-sand, which started the whole action. The general character of the stratification in this area does not support the postulate of a delta with steepening slopes. The following are a few suggestions:

1. Excessive local deposition and removal of support through erosion of adjacent deposits.

2. Disproportional load, in this case on the prolongation of the disturbed mass, for we have already affirmed the absence of deposits immediately above the drift sand at the spot observed. Also, the structure now developed differs much

[12] *Ibid.*, p. 361.

from the examples of intraformational disturbance discussed by E. M. Kindle.[13]

3. In the submarine flank of the Miocene land area mentioned above, quicksand might have originated through expulsion of water from dipping strata.

4. The best explanation which can be given at the moment seems to be the following: Clay sediments may undergo considerable compaction, as is well known. Now compaction, without real consolidation of the "intermediate" marly mud, due to increasing sandy deposits above, will be accompanied by expulsion of water which will rise into the superposed sand layer. A slight inclination of the sea bottom would suffice for flowing, and balance might be disturbed by slight downward movements common to sedimentary basins, giving an increase of inclination. The symmetry of the sand lenses seems to indicate flowage from the sides of a very slight sea-floor depression toward its center. This interpretation seems most likely, but we must await further detailed investigation of the transition between the disturbed strata and undisturbed equivalents near by. The stratification of the intermediate marl is a result of compaction. It certainly does not represent any initial stratification before the flowage.

R. H. Sorby[14] and S. M. K. Henderson[15] have described phenomena resembling Brueren's example to a certain extent, although the structures are developed on a scale twenty-five to thirty times smaller. Sorby discussed wavelike tuffaceous layers with normal lower surface. The waves are overthrown in one direction like breakers, indicating the direction of currents. They are covered with other tuffaceous deposits. According to Sorby, the breakers originated from disturbance of semiliquid mud on the sea bottom, washed by a current of water (started by a volcanic disturbance), which carried fresh, coarser ashes. Parts of the breakers were involved by the flowing mass. In our opinion we must also bear in mind the possibility of heavy rains on ash deposits of volcanic slopes developing suspensions, which, indeed, might act upon the fresh deposits of the submarine slope in the above-mentioned way.

Henderson described the result of a sand suspension flowing over somewhat consolidated mud. These structures closely resemble those studied by Sorby. Henderson attributed the disturbances to seismic causes connected with the development of a geosyncline. As is pointed out above, the same might apply to Brueren's case. In many respects Henderson's example may be best compared with Brueren's.

HELVETIAN SUBMARINE SLIDING IN THE TURIN HILLS (MONFERRATO)

a) In the Turin Tertiary the author discovered another example of subaqueous movement of strata near the picturesque village of Casalborgone (Fig. 3, *b*) about 20 km. east-northeast of Turin (cf. Fig. 6). This disturbance was briefly discussed in 1941.[16] Figure 4 of the present paper shows the section

[13] "Deformation of Unconsolidated Beds in Nova Scotia and Southern Ontario," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 323–34.

[14] "An Application of Quantitative Methods to the Study of Rocks," *Quart. Jour. Geol. Soc. London*, Vol. LXIV (1908), pp. 197–233 (cf. pp. 196–97, Pl. 14).

[15] "Ordovician Submarine Disturbances in the Girvan District," *Trans. Roy. Soc. Edinburgh*, Vol. LVIII (1935), pp. 487–509 (cf. p. 502, Pl. 2, Fig. 3).

[16] Beets, *De geologie van het westelijk deel van het Heuvelland van Monferrato tusschen Turijn en Murisengo*, pp. 60, 88–89, Pl. 2, Fig. 1; "Die Geologie des westlichen Teiles der Berge von Monferrato zwischen Turin und Murisengo," pp. 219 (n. 52), 237 (Fig. 9), 238.

which may be studied well in the steep slope north of the main road from Airali to Casalborgone (cf. Figs. 3, 5, and 6). The simple geology of this area may be described as follows: We are here about in the center of the shallow and tectonically very simple syncline of Casalborgone, in a sandy series of marine Helvetian, which shows, horizontally as well as vertically, considerable lithologic variation. Near the place of the photo (Fig. 4), in the flanks of the almost isolated hill of Casalborgone, we observe a lower, undisturbed series of alternating sands and marls (*s-m* in the next pages). This series is covered by a relatively thick sand layer and other marly sands as well as by irregularly intercalated marl layers. The disturbed strata did not undergo tectonic folding, as they are in an almost unfolded part of the syncline. The lower boundary of the folded series must represent a gliding horizon; the upper surface is a slightly wavy erosion unconformity.

The explanation of the disturbance is that a certain part of the upper layers of a series of sand and marl sediments, deposited on a submarine slope, underwent a downward sliding movement. The sliding plane may either have developed mechanically or, more probably, was the

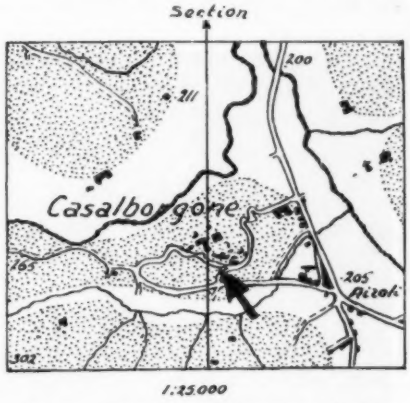

FIG. 3*a*.—The center of the syncline of Casalborgone in the Turin Hills (*dotted:* Helvetian deposits; *white:* alluvial Quaternary). The arrow locates Fig. 4 and the direction of the photograph.

FIG. 3*b*.—The hill of Casalborgone, seen from the east. Note arrow. (Photograph by the author.)

surface of the sediments in front of the sliding mass (cf. Twenhofel's idea).[17] The folds apparently originated from stowage, combined with slackening speed of the sliding mass. We do not know at present whether the folding is everywhere slight, but we may suppose that the front of the slide developed some beveled the folds. The boundary certainly does not represent a tectonic thrust plane, which, moreover, could not be expected in this simple and shallow syncline. This erosion was a submarine one, as the sliding series moved toward a deeper part of the sea floor. Subaerial erosion is very improbable. According to

FIG. 4.—Subaqueous sliding in Helvetian strata of Casalborgone in the Turin Hills, Monferrato, Piedmont. (Photograph by the author.)

"breakers" against the underlying strata which acted as a brake. According to the strike of the folded strata (northeast-southwest), the sliding was directed to the southeast or the northwest. Other features point to the former direction.

The nature of the surface of contact between the folded and unfolded superposed strata indicates that the sliding mass has been subject to erosion, which the nature of the strata in the neighborhood and the Helvetian sedimentation in general, there is no evidence for a sudden fall and rise of the sea-level.

This erosion seems to contradict the enormous deposition of Alpine clastics in the Turin basin during Helvetian time; but here there was only a very short period of erosion, which was connected intimately with the sliding itself. It is explained by an intensive turbulent action of the sea water during the sliding, accompanied by the rise of a suspen-

[17] W. H. Twenhofel, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins Co., 1932), p. 742, Fig. 109.

sion caused by the whirling of unconsolidated sediments. From frontal to posterior part of the slide the erosion of its surface increased. A suspension of this kind will act with strong erosive force,[18] and a second suspension will serve as a lubricant below the sliding mass.

A "whirl-zone," the deposition of the erosive suspended material after movement had ceased, should have been developed chiefly behind the sliding mass and afterward have been partly eroded during the transport of the sand grains of the first superposed layer. So the present contact between folded and overlying unfolded strata may be considered

FIG. 5.—Section through the syncline of Casalborgone. The asterisk indicates the locality of Fig. 4

the result of two erosive actions separated by a short period of deposition. Perhaps the whole whirl-zone was eroded during the second erosion, for we could not verify it.

In contrast to the above-mentioned phenomenon, we observe in the present case an increase in number and thickness of strata[19] at the very spot of the sliding mass, while somewhere in the neighborhood a decrease in number of strata must exist (not observed).

b) When trying to explain the subaqueous "solifluction,"[20] we must consider the possible cause. Unlike most cases of sliding, this example furnishes us with sufficient proof in the development of the sedimentary basin of Casalborgone.[21] We therefore give a brief synopsis of the Helvetian sedimentation in the Turin Basin.[22]

The Helvetian deposition followed after the quiet sedimentation of the Langhian stage. In the western part of the Turin Basin it is characterized by the deposition of an enormous amount of coarse-grained clastics, derived from the huge Pennine chain, which formed a land area during the whole Tertiary. In the

[18] As the sliding mass was folded, that is to say at the spot figured here, it was easy to recognize an erosion surface. But we saw the sharp contact first at another place where pseudo-concordance was observed. There we could only think of erosion in a sense which must be called normal, for, as we pointed out in 1942, in accordance with other investigators (Winkler, cited below), we often must consider sharp boundaries between concordant strata as the result of erosive forces. In the above-mentioned case the contact was so sharp that we followed it and soon discovered the unconformity. Cf. R. Brinkmann, "Über die Schichtung und ihre Bedingungen," *Fortschr. Geol. u. Pal.*, Vol. XI (1932), pp. 187–219; A. Kumm, "Schicht, Bank, Lager," *Geol. Rundschau*, Vol. XXIII A (1932), pp. 186–200; C. Beets, "Das Schichtungsproblem, ein Beitrag aus den Turiner Bergen ('Colli Torinesi')," *Leidsche Geol. Meded.*, Vol. XIII (1942), pp. 39–62.

[19] This increase results, according to Heim, from (1) direct superposition by the sliding mass and (2) deposition of the suspension which arises from the sliding (cf. A. Heim, "Über submarine Denudation und chemische Sedimente," *Geol. Rundschau*, Vol. XV [1924], pp. 1–47 [cf. p. 21]).

[20] Solifluction: see Andersson. Heim (see ftn. 19) introduced the term "subsolifluction" for phenomena in the sense of the one discussed here, but Schaffer did not appreciate this term. Cf. J. G. Andersson, "Solifluction, a Component of Subaerial Denudation," *Jour. Geol.*, Vol. XIV (1906), pp. 91–112; F. X. Schaffer, "Über subaquatische Rutschungen," *Centralbl. f. Min., etc.* (1916), pp. 22–24.

[21] "Auch die Gesteine sind abhängig von ihrer Umwelt und nur dann genetisch zu erklären, wenn man sie nich nur für sich, sondern im Rahmen von Abtragungsgebiet, Transportbahn und Sedimentationsraum betrachtet, alle Eigenschaften der einzelnen betrachtend" (Kayser, pp. 405–6 of ftn. 3).

[22] Beets, ftn. 2.

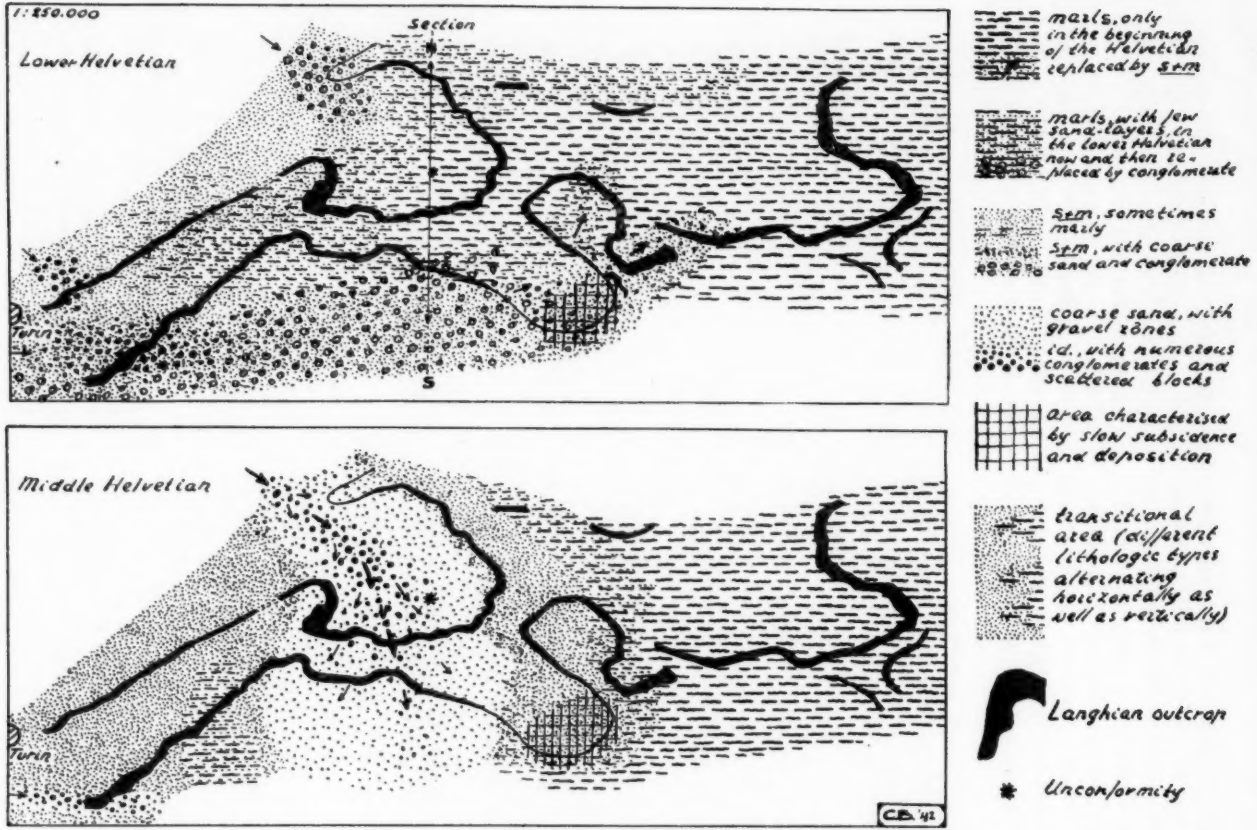
1:250.000
Section
Lower Helvetian
Turin
S
Middle Helvetian
Turin
CB '42
marls, only in the beginning of the Helvetian replaced by S+m
marls, with few sand-layers, in the lower Helvetian now and then replaced by conglomerate
S+m, sometimes marly
S+m, with coarse sand and conglomerate
coarse sand, with gravel zones
cd., with numerous conglomerates and scattered blocks
area characterised by slow subsidence and deposition
transitional area (different lithologic types alternating horizontally as well as vertically)
Langhian outcrop
Unconformity

FIG. 6.—Summary of the spreading of several lithologic types in the Turin basin during part of the Helvetian stage. The maps represent the western part (Turin Hills) of Monferrato. The Langhian outcrops were used as basis for the paleogeography. The section indicated on the map for Lower Helvetian is magnified in Fig. 5 (Sec. 19 of the papers by the author, 1941). The asterisk agrees with the one in Fig. 5.

lower Helvetian (cf. Fig. 6) large parts of the basin were covered with marly sediments. Over a southern shallow zone, which already existed in Lower Miocene and Langhian, coarse deposits accumulated. In the eastern part of this zone we observe an oval structure, the so-called "dome of Serra," where the Mesozoic "Argille scagliose" was rising regularly ("diapyrous"), causing slow subsidence and sedimentation. In a short period between the two which are mapped, the sedimentation of the southern strip was replaced by that of a series of *s-m* deposits.

In the Middle Helvetian (Fig. 6, below) this zone was again occupied by coarse-grained sedimentation, but now only in the west. It must be emphasized that the dome of Serra played the same part before the Helvetian (post-Eocene) and after it, until Pliocene time at least.

The delta built in the northwestern part of the basin will stand in direct connection with the slide near Casalborgone. This delta had reached the mapped area in Lower Miocene time. In the following Langhian stage it was relatively inactive, but in the Lower Helvetian coarse deposition went on. Around the front of the delta *s-m* deposits and marls were laid down.

In a somewhat younger period (not mapped), the delta deposited finer sediments, namely, *s-m*, in accordance with the finer sedimentation in the southern zone (see above). Soon the coarser deposition reappeared, and the delta tongue, the main transport zone, was shifted somewhat to the south. At about the same time the *s-m* deposits of Casalborgone were laid down as part of a large areal accumulation in front of the delta.

This delta was characterized by rapid deposition, and it spread particularly in a southeastern and southern direction. Figure 6 shows the delta in extreme development. Enormous amounts of coarse sand deposits, gravel, and conglomeratic zones were laid down, and also numerous scattered huge blocks, which suggest the existence of large "mud" flows (streams of mud, sand, gravel, pebbles, and blocks),[23] like recent examples, fan-shaped before a relatively narrow transport zone.

This short summary of the Helvetian sedimentation, based on detailed investigation of the lithologic variation in the Turin Basin, may suffice.

If we compare the situation of the sliding mass with the development of the delta in space and time, it is permissible to assume close connection between them. We may accept the following explanation: The *s-m* deposits of Casalborgone belonged to the submarine frontal slopes of the delta, which advanced southeastward and southward. At Casalborgone first marls, afterward *s-m*, coarse sand, and coarser deltaic sediments, respectively, were deposited. The cause of the sliding[24] was probably only

[23] Twenhofel, pp. 93–94 and Figs. 6–7 of ftn. 17.

[24] We might suggest seismic causes, for these are known to play a part in recent ruptures of telegraph cables: cf. Milne and also Yamasaki. Aldinger does not like assuming seismic causes, as these cannot be proved in fossil examples. Occurrence of sliding is recognized in many tectonic processes (cf. Baldry, Brown, Marin, and Kuenen's summary).

Cf. J. Milne, "Sub-oceanic Changes," *Geogr. Jour.*, Vol. X (1897), pp. 129–46, 259–89; N. Yamasaki, "Physiographical Studies of the Great Earthquake of the Kwânto District, 1923," *Jour. Fac. Sci., Imp. Univ. Tokyo*, Sec. 2, Vol. II (1926), pp. 76–119; H. Aldinger, "Über die Entstehung der Kalkschiefer des oberen Weissen Jura von Nusplingen in Württemberg," *Centralbl. f. Minn., etc.* (1930), B, pp. 257–67 (cf. p. 264); R. A. Baldry, "The Clay Pebble Bed of Ancon, Ecuador," *Geol. Mag.*, Vol. LXIX (1932), pp. 45–46; R. A. Baldry, "Slip-Planes and Breccia Zones in the Tertiary Rocks of Peru," *Quart. Jour. Geol. Soc. London*, Vol. XCIV (1938), pp. 347–58; C. B. Brown, "On a Theory of Gravitational Sliding Applied to the Tertiary of Ancon, Ecuador," *Quart. Jour. Geol.*

Lower Helvetian is magnified in Fig. 5 (Sec. 19 of the papers by the author, 1941). The asterisk agrees with the one in Fig. 5.

the creation of too steep an inclination through rapid sedimentation in the frontal part of the delta,[25] perhaps combined with one of the many subsidences of the sea bottom which are responsible for cyclic stratification of the sediments.[26] A labile part of the sediments slid down to deeper water.[27] As already stated, the slide moved in either a northwest or a southeast direction (according to the strike of the folded strata). The delta indicates sliding in a southeasterly direction.

We do not know the distance of the sliding movement, but apparently the deepest place in a shallow basin between the starting-point of the slide and the dome of Serra—which acted more as resistance against subsidence than as a real topographic rise—was at Casalborgone. It is impossible to reconstruct with any certainty the bathymetry of the Helvetian basin at the moment of sliding.[28] We know no more than that the sediments described were shelf deposits; but, from the distribution of gravels and conglomeratic zones,[29] we may suppose the coastal line to have been about over the small anticline northwest of Casalborgone. The distance from this coastline to Casalborgone would amount to 6 km. at the most. If we estimate the depth of the sea basin at 200 meters (max.), then the average inclination of the submarine delta-front would have been 3° at a rough estimate.

According to A. Heim[30] and Grabau, a slope of 4.4 per cent (2.5°) will suffice for sliding; but, according to Escher,[31] this figure is too low because of the complication of extra burden by buildings in the case of the recent Swiss lake slides discussed by Heim. He was of the opinion, however, that very small inclinations might suffice for sliding,[32] stimulated by increasing thickness of the labile strata.[33] On the other hand, the

Soc. London, Vol. XCIV (1938), pp. 359–68; R. Martin, *Leidsche Geol. Meded.*, Vol. VIII, pp. 55–154; Ph. H. Kuenen, "Geological Interpretation of the Bathymetric Results," *The Snellius Exped. 1929–30*, Vol. V (Geol. Res.), Part I (1935).

[25] A possibility suggested by Andree (cf. K. Andree, *Geologie des Meeresbodens*, Vol. II: *Bornträger* [1920], p. 272, and p. 262 of ftn. 6 [1923]); cf. p. 740 of ftn. 17.

[26] See Beets, ftn. 18.

[27] It may be added here that in many cases of strange combinations, either of lithologic or of faunistic character, subaqueous sliding is supposed to have played a part. Cf. Twenhofel, p. 740 of ftn. 17; Andree, p. 273 of ftn. 25; Kuenen, p. 71 of ftn. 24; and W. P. Woodring, *Carnegie Inst. Wash. Publ.*, Nos. 366, 385 (1925–28). Rutsch (*Eclogae geol. Helvetiae*, Vol. XXIV [1931], pp. 258–59) has disrupted Woodring's suppositions.

[28] Andree, p. 288 of ftn. 25.

[29] See geologic maps, Beets, ftn. 2.

[30] "Über rezente und fossile subaquatische Rutschungen und deren lithologische Bedeutung," *Neues Jahrb. f. Min., etc.* (1908), pp. 136–57.

[31] B. G. Escher, "Beschouwingen over het opvullingsmechanisme van diepzeeslenken," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. en Koloniën, Geol. Ser.*, Vol. III (1916), pp. 79–88.

[32] Escher (see ftn. 31) and Horn accepted submarine sliding as an important agent in the accumulation of sediments in deep-sea depressions (inclinations 5°–20°, in most cases 4°–10°). Submarine slidings would explain peculiar alternation of bathyalic and neritic sediments. Arnold Heim (p. 21 of ftn. 19) suggests: "Wie gross muss daher erst die Bedeutung (of the slidings) sein für die riesigen Böschungen nach den Tiefseegräben, die bis zu 36° Steilheit erreichen." In 1941 (Beets, p. 238 of ftn. 2) we cited Heim's paper of 1924 incorrectly in connection with the Turin Basin, for Heim's conclusions did not apply to basins of the Turin type.

When considering cross-sections of sea basins, Kuenen (see ftn. 24) cannot accept Heim's view cited above. In exceptional cases only, neritic sediments would reach the great deeps. According to Kuenen, the few observations on sliding in fossil state are because of the rarity of the phenomenon. Cf. E. Horn, "Über die geologische Bedeutung der Tiefseegräben," *Geol. Rundschau*, Vol. V (1915), pp. 422–48.

[33] See Twenhofel, p. 741 of ftn. 17, and Kuenen, p. 71 (pp. 69–72) of ftn. 24.

data collected by the "Snellius" expedition have indicated that some sediments show surprising stability on steep slopes. As Kuenen has pointed out, marine sediments in general will attain a certain consolidation more quickly than will nonmarine sediments. The slow deposition of the fine-grained sediments discussed by Kuenen would allow more time for consolidating processes than the rapid deposition of other deposits, before their inclination became sufficient for sliding. The inclinations mentioned by Kuenen are extremely high: 7°–34° for deposits of 1 meter in thickness in one of the very active seismic areas of the earth. Unfortunately, we cannot compare these data for fine-grained sediments with the conditions in the Turin case. On the other hand, Twenhofel[34] has cited high angles for subaqueous sandy deposits, collected by Miss Draper: 33°–43° (coarse sand) and 35°–38° (finer sand). And, furthermore, Kuenen has pointed out[35] that perhaps he observed only the stable lower portions of a much thicker series of strata, the upper portions having repeatedly slid away: "Our investigation therefore only proves the possibility of a certain amount of accumulation (1 m.) but does not exclude the possibility of slides, either sudden or gradual." From the data available we may conclude that more investigations of recent and fossil slides are needed before reliable comparisons can be made.

The partial consolidation of the sliding mass near Casalborgone is proved by the structures presented.[36] Consolidation is the first condition for development of the finest examples of disturbed strata.[37]

The final event which led to sliding is doubtful. It may have been seismic or only one of the supposed small subsidences. In the latter case we might expect many more slides in the Turin Tertiary, as in all basins with rapid deposition.[38] So Aldinger[39] seeks to explain sliding structures by referring to Klüpfel's well-known studies of Jurassic sediments, in which frequent rise and fall of sea-level played an important part. But neither elsewhere in the Helvetian basin of Casalborgone, which may be studied in numerous exposures, nor in other series in the Turin Basin did we observe slides comparable with that at Casalborgone. The sliding in the frontal part of the delta[40] might be exceptional.

OTHER CASES OF SOMEWHAT SIMILAR STRUCTURES

Although subaqueous slides in unconsolidated strata are likely to be overlooked in most cases, it is astonishing to note the variety of sliding structures ob-

[34] P. 604 of ftn. 17.

[35] P. 71 of ftn. 24.

[36] Escher (p. 80 of ftn. 31) has expressed the opinion that preservation of structure of sliding sediments is exceptional. Of course, this view applies in the first place to quick sliding actions over great distances, from the neritic regions to deep-sea basins.

[37] F. Hahn, "Untermeerische Gleitungen bei Trenton Falls (Nord-Amerika) und ihr Verhältnis zu ähnlichen Strömungsbildern," *Neues Jahrb. f. Min., etc.*, add. Vol. XXXVI (1912), pp. 1–41 (cf. p. 15).

[38] Hadding, p. 380 of ftn. 9.

[39] See ftn. 24.

[40] The reader will observe that the delta discussed does not agree with the usual textbook picture of delta structure. This is due, to a certain degree, to the special mudflow character of the supply in the Turin example. From time to time, in Lower and especially Middle Helvetian time, this delta reminds us of the Alpine "Wildbach" delta type. These fan-shaped accumulations of clastics on their part remind us of submarine volcanic slopes which show sliding as well (cf. Kuenen). See P. D. Trask, *Recent Marine Sediments: A Symposium* (London: Murbury, 1939); Ph. H. Kuenen, "Contributions to the Geology of the East Indies from the Snellius Expedition, Part I, Volcanoes," *Leidsche Geol. Meded.*, Vol. VII (1935), pp. 273–331.

served by a great number of authors. But we encountered no structures which might be compared directly with our delta slide. Aldinger[41] observed scale-like foldings in Jurassic strata of Württemberg. Bailey, Collet, and Field[42] described several intraformational conglomerates in Paleozoic rocks near Quebec, in close connection with tectonic lines. These phenomena and those mentioned by Bailey and Weir[43] in Kimmeridgian strata of East Sutherland are not comparable. The same applies to the interesting structures discovered by Musper[44] in the Padang Highlands, Sumatra; to slidings in the Pilomasin basin, Sumatra, by Van Bemmelen;[45] and to the beautiful sliding structures in tuffaceous strata of the Isle of Ischia, Mediterranean, by Rittmann.[46] Endriss[47] made similar observations. Brown[48] has discussed a fine example of an insufficiently consolidated lime-mud, with intraformational layers of limestone pebbles, folded by sliding action. Cartwright[49] also discussed sliding sediments containing pebbles,[50] which are also known from other American deposits. Von Freiberg[51] observed unconformities in a series of the Thuringian Basin with scale-like structures which were eroded. Hadding[52] discussed several interesting phenomena rather unlike, however, the slide of Casalborgone. Hahn[53] described, among others, three deformed zones max. thickness 12 meters) between undisturbed series in Ordovician rocks near Trenton Falls. He suggested relation to tectonic movements. Miller[54] referred these to hard-rock faulting.

Among the other cases discussed by Hahn, his Figure 1 (after Reis),[55] from German Muschelkalk, resembles our Figure 4. Miller has discussed more examples. One of these was discovered by Logan[56] (cf. also Hahn). Henderson[57] and Hölder[58] have discussed some struc-

[41] See ftn. 24.

[42] E. B. Bailey, L. W. Collet, and R. M. Field, "Paleozoic Submarine Landslips near Quebec City," *Jour. Geol.*, Vol. XXXVI (1928), pp. 577–614.

[43] E. B. Bailey and J. Weir, "Submarine Faulting in Kimmeridgian Times, East Sutherland," *Trans. Roy. Soc. Edinburgh*, Vol. LVII, II (1932–33), pp. 429–68.

[44] K. A. F. R. Musper, "Die fischführende Breccien- und Mergelschieferabteilung des Tertiärs der Padanger Hochlande (Mittel-Sumatra)," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. e. Koloniën, Geol. Ser.*, Vol. XI (1935), pp. 145–88.

[45] R. W. van Bemmelen, "Het Boekit Mapas-Pematang Semoet vulkanisme (S. Sumatra)," *Verhand. Geol. Mijnbouwk. Gen. v. Ned. e. Koloniën. Geol. Ser.*, Vol. IX (1931), pp. 57–76.

[46] A. Rittmann, "Geologie der Insel Ischia," *Zeitschr. f. Vulkan.*, Add. Vol. VI (1930).

[47] K. Endriss, "Geologie des Randecker Maars und des Schopflocher Riedes," *Zeitschr. d. D. Geol. Ges.*, Vol. XLI (1889), pp. 83–126.

[48] T. C. Brown, "Notes on the Origin of Certain Paleozoic Sediments, Illustrated by the Cambrian and Ordovician Rocks of Center County, Pennsylvania," *Jour. Geol.*, Vol. XXI (1913), pp. 232–50.

[49] L. D. Cartwright, "Sedimentation in the Pico Formation in the Ventura Quadrangle, California," *Bull. Amer. Ass. Pet. Geol.*, Vol. XII (1928), pp. 235–69.

[50] Twenhofel, p. 744 of ftn. 17.

[51] B. von Freiberg, "Der Aufbau des unteren Wellenkalkes im Thüringer Becken," *Neues Jahrb. f. Min., etc.*, Add. Vol. XLV (1921), pp. 214–74.

[52] See ftn. 9.

[53] See ftn. 37.

[54] W. J. Miller, "Slightly Folded between Nonfolded Strata at Trenton Falls, NewYork," *Jour. Geol.*, Vol. XVI (1908), pp. 428–33.

[55] O. M. Reis, "Beobachtungen über Schichtenfolge und Gesteinsausbildungen in der fränkischen Unteren Trias," *Geognost. Jahresh.*, Vol. XXII, Part I (1910) (*non vidi*).

[56] W. E. Logan, *Geology of Canada* (1863) (*non vidi*).

[57] See p. 506, Fig. 19, of ftn. 15.

[58] H. Hölder, "Geologische Untersuchungen in der Umbebung von Lauchheim (Ostalb)," *Neues Jahrb. f. Min., etc.*, Add. Vol. LXXXVI (1942), pp. 315–89 (cf. esp., pp. 341–43, Pl. 25).

tures which, in general, are not comparable. Hölder also considered an occurrence reported by Krumbeck,[59] who has observed strong foldings of various kinds. Kindle[60] has discussed slidings in the tidal zone, which he explained by differential weight of more consolidated and heavier material on soft sediments.[61] Klingner[62] presented a beautiful example of rolling (sliding) sediments, a variant of the snowball structures mentioned by Hadding. Knauer[63] considered finely folded sediments between regularly stratified beds; Kraus[64] structures in Flysch strata of Oberammergau, Bavaria, his Figure 1 resembling our Figure 4.

Krejci-Graf and Liebus[65] briefly mentioned flow structures and sliding folds in Rumanian Upper Eocene strata; Lukovic,[66] Samatrian disturbed and folded strata (according to a review). Simon[67] discussed subaqueous sliding folds in the Upper Cambrian strata near Seville, Spain; De Terra,[68] peculiar structures previously discussed by Knight.[69] Leuchs[70] has described, among others, an interesting small-scale structure. Steuer[71] discussed slidings in Oligocene deposits of Rheinhessen, Germany; and Winkler[72] described Upper Sarmatian structures referred to submarine sliding of fresh lime-mud material, afterward superposed by coarse deposits resting on a sharp plane of erosion. For Knight and Rothpletz,[73] see Twenhofel.[74] Other papers are cited below.[75] Lippert[76] has pub-

[59] L. Krumbeck, "Faltung, untermeerische Gleitfaltung und Gleitstauchung am Tithon der Altmühlalb," *Neues Jahrb. f. Min., etc.*, Add. Vol. LX (1928), pp. 113–64.

[60] See ftn. 13.

[61] Cf. also W. Häntzschel, "Die Schichtungsformen rezenter Flachmeer-Ablagerungen im Jade-Gebiet," *Senckenbergiana*, Vol. XVIII (1936), pp. 316–56 (cf. p. 352); *idem*, "Senkrecht gestellte Schichtung in Watt-Ablagerungen," *ibid.*, Vol. XX (1938), pp. 43–48.

[62] F. E. Klingner, "Sediment-Rollen (Unterwasser-Gleitung) im Muschelsandstein bei Saarlauetern," *Senckenbergiana*, Vol. XXI (1939), pp. 311–13.

[63] J. Knauer, "Überzählige Schichtablagerung und Scheintektonik," *Abhandl. Geol. Landesunters. d. Bayr. Oberbergamt*, Vol. XVII (1935), pp. 47–55.

[64] E. Kraus, "Über Sandsteinwülste," *Zeitschr. d. D. Geol. Ges.*, Vol. LXXXVII (1935), pp. 354–60.

[65] K. Krejci-Graf and A. Liebus, "Tertiäre Foraminiferen aus den rumänischen Ölgebieten," *Neues Jahrb. f. Min., etc.*, Add. Vol. LXXIV (1935), pp. 118–56.

[66] M. T. Lukovic, "Fossil Landslides on the Right Bank of the Danube near Beograd" (Engl. summary), *Vesnik Geol. Inst.*, Vol. VI (1938), pp. 261–65 (*non vidi*).

[67] W. Simon, "Lithogenesis kambrischer Kalke der Sierra Morena (Spanien)," *Senckenbergiana*, Vol. XXI (1939), pp. 297–311.

[68] H. de Terra, "Structural Features of Gliding Strata," *Amer. Jour. Sci.*, (5), Vol. XXI (1931), pp. 204–13.

[69] S. H. Knight, "The Fountain and Caspar Formations in the Laramie Basin," *Univ. Wyoming Publ., Geol.*, Vol. I (1929), pp. 74–78 (*non vidi*).

[70] K. Leuchs, "Feinschichten, Gleitfaltung, Algenrasen und Trümmerlagen im Wettersteinkalk," *Chemie d. Erde*, Vol. VII (1932), pp. 95–112 (cf. p. 97, Fig. 3).

[71] A. Steuer, "Über Rutschungen im Cyrenenmergel bei Mülschim und anderen Orten in Rheinhessen," *Notizbl. d. Ver. f. Erdk. u. Geol. Landesanst. Darmstadt*, Vol. IV, No. XXXI (1910), pp. 106–14 (*non vidi*).

[72] A. Winkler, "Über die sarmatischen und pontischen Ablagerungen im Südostteil des Steirischen Beckens," *Jahrb. Geol. Bundesanst, Wien*, Vol. LXXVII (1927), pp. 393–456.

[73] A. Rothpletz, "Meine Beobachtungen über den Sparagmit und Birikalk am Mjösen in Norwegen," *Sitzungsber. K. Bayr. Ak. d. Wiss. München, math. naturwiss. Kl.*, Vol. XV (1910), pp. 3–66.

[74] See pp. 743–44 of ftn. 17.

[75] A. Briart, "Notes sur les mouvements parallèles des roches stratifiées," *Ann. Soc. Géol. Belgique*, Vol. XVII (1890), pp. 129–35; E. R. Cumings and R. R. Schrock, "The Geology of the Silurian Rocks of Northern Indiana," *Direct. Geol. Dept. Conserv. Indiana*, Publ. No. 75 (1928) (*non vidi*);

[Note 75 continued on next page]

[76] See ftn. 11.

lished an important paper on disturbances of strata, also containing a useful classification of the different phenomena mentioned above. Interesting cases of subaqueous movement were treated in this paper.

FURTHER EXAMPLES OF DISTURBANCE OF STRATA IN THE TURIN TERTIARY

Nontectonically disturbed sediments are exposed at several places in the Turin Hills. In 1941 we discussed clay balls.[77] Other structures call for special attention to a paper by Häntzschel,[78] of which we were not aware in 1941. Häntzschel has discovered chaotic stratification caused by tidal gully action in recent North Sea shoal regions: sliding of small packets of slightly consolidated strata (see below). Other proofs of gully action, discovered in a Helvetian shoal region near the dome of Serra (mentioned above), were described in 1941 and compared with Häntzschel's descriptions of recent North Sea examples.[79] One of the features was a cross-section of a tidal gully, showing Alpine pebbles, which had been shifted back and forth in the tidal zone. Afterward, the gully and its surroundings were eroded and covered by other sediments.[80]

The dome of Serra was one of the shallowest portions of the Helvetian Basin. Besides the gully, we observed further proofs of the existence of a shoal region, which may be compared with the southern North Sea coasts. At many places west of the dome of Serra, but only so far as coarse deposits are known in the Lower Helvetian, we observed a disturbed stratification which reminds us strikingly of the structures figured by Häntzschel, viz., chaotic arrangement of fragments of stratified sediments. We especially saw sections resembling Häntzschel's Figure 3 in all respects. Häntzschel explained this disturbed stratification as follows: Washing of strata in the steep sides of gullies, which are well known in the tidal zone of the North Sea shoal regions, is involved in the gradual shifting of the course of the gullies. Through this operation of small gradual movements, sediment packets, which are more or less consolidated, glide down and ac-

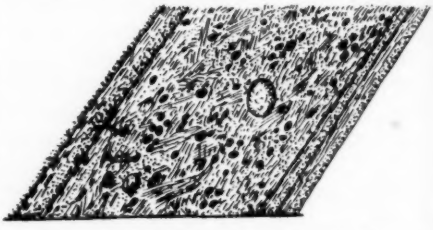

FIG. 7.—Middle Tongrian near Casa Nicolletti in the eastern Turin Hills, containing Alpine pebbles and showing "gully structures." Scale about 1:80.

P. E. Kent, "Contemporaneous Disturbances in Lacustrine Beds in Kenya," *Geol. Mag.*, Vol. LXXXII (1945), pp. 130–35; P. G. Kraus, "Weitere Beobachtungen im Tertiär und Diluvium des Niederrheins," *Jahrb. Preuss. Geol. Landesanst.*, Vol. XXXVIII, Part I (1919), pp. 183–200; F. Lotze, "Zur Erklärung der Querplattung (Sigmoidalklüftung) im Wellenkalk," *Centrallbl. f. Min., etc., B* (1932), pp. 300–307; H. Nathan, "Geologische Untersuchungen im Ries," *Neues Jahrb. f. Min., etc.*, Add. Vol. LIII (1925), pp. 31–97; N. B. Vassoevich, "On the Problem of the Large Submarine Landslips (Eng. summary)," *Trans. Oil Inst. Moskau Leningrad* (1935) (*non vidi*); R. Weyl, "Stratigraphie und Tektonik der Grundgebirgsgrenze zwischen Kinzig und Elz im mittleren Schwarzwald," *Badische Geol. Abh.*, Vol. VIII, Part I–II (1936), pp. 46–126 (*non vidi*).

[77] See Beets, *De geologie van het westelijk* . . . . , p. 33 (Pl. I, Fig. 1), 49, 90–91 (Figs. 4, 5); and Beets, "Die Geologie . . . . ," pp. 206 (Fig. 3), 207, 214, 238–40 (Figs. 10–11), of ftn. 2.

[78] See ftn. 61 (1938).

[79] See ftn. 61 (1936).

[80] See Beets, *De geologie* . . . . , pp. 92–93, Fig. 6; and Beets, "Die Geologie . . . . ," p. 240, Fig. 12, of ftn. 2.

cumulate in disorder in the bed which is being left by the shifting gully. This explanation will apply to the Helvetian structures near the dome of Serra as well.

As stated in 1941,[81] chaotic sediment packets are also known from part of the Middle Tongrian in the eastern Turin Hills. We here repeat as Figure 7 the sketch published in 1941, which shows jumbled marl packets, clay balls of local derivation,[82] and pebbles of Alpine origin.

The geologic data point to a near-by coastal line, along which Alpine pebbles were transported from west to east and deposited mainly south of Casa Nicoletti (this spot lies north of the main transport zone, which started in the delta zone along the Pennine Alps and followed the south coast of an anticlinal structure in the Turin basin, ending in the vicinity of Casa Nicoletti).[83] Now and then Alpine pebbles and clay balls were transported to the marly region of Casa Nicoletti, where they were mixed with locally formed marl packets. In 1941 we tried to explain the marl packets by washing by "sea-currents"; but now we prefer to explain them, including the whole sedimentation near Casa Nicoletti, by a special kind of current operation, viz.; by gully action in a broad tidal zone along the eastern extremity of the anticlinal structure which formed a land-strip during Oligocene time. The Alpine pebbles were transported from the southern accumulation of coarse deposits by gully action, which, moreover, at Casa Nicoletti caused chaotic stratification of marly sediments. The clay balls were derived from deposits in the vicinity of their present locality.

[81] See Beets, *De geologie* . . . . , p. 90, Fig. 4; Beets, "Die Geologie . . . . ," p. 238, Fig. 10, of ftn. 2.

[82] Cf. Häntzschel's Fig. 1 of ftn. 61 (1938).

[83] See Beets, *De geologie* . . . . , p. 80, Map I, and "Die Geologie . . . . ," p. 230, Map I, of ftn. 2.

ORIGIN OF THE LACKAWANNA BASIN, PENNSYLVANIA[1]

BRADFORD WILLARD
Lehigh University, Bethlehem, Pennsylvania

ABSTRACT

The Lackawanna Basin or Northern Anthracite Field lies in northeastern Pennsylvania between the Allegheny Plateau on the west and the Pocono Plateau on the east. Structurally, it resembles similar long, narrow synclines of the Appalachians, but its trend is different. Data on thicknesses of formations indicate a marked thinning of the Mississippian under the basin. Its presence is attributed to this thinning, because during the Appalachian Revolution here was a region of structural weakness.

LOCATION

If one examines a geologic map of Pennsylvania, he will see in the northeastern quarter of the state the Anthracite Fields, producing area of most of our "hard coal." A region of folded strata, the structural trend and the physiographic expression of the fields conform with those of the Appalachian Mountains, of which they form a part. However, like the proverbial rule, this last statement has its exception. Springing from the northeastern corner of the main body of the Anthracite Fields, and extending northeastward for some 70 miles nearly to the New York State line, is a long, narrow syncline called the Northern Anthracite Field or the Lackawanna Basin. Wedged between the Allegheny Plateau on the west and the Pocono Plateau on the east, this anomalous structure has the characteristics of the larger, fusiform Appalachian synclinal basins; but its northeast by southwest alignment fails to conform with the more nearly east-west trend of the mountains of northeastern Pennsylvania. To appreciate more fully this anomaly, note the general physiographic aspect of the northwestern three-fourths of the state.

[1] Published with the permission of the State Geologist of Pennsylvania.

PHYSIOGRAPHIC SETTING

The Allegheny Plateau embraces most of the western half of Pennsylvania and extends into the northeastern quarter of the state. It is separated on the east and south from the ridges and valleys of the Appalachian Mountains by an escarpment, the Allegheny Front. From the state's south-central border, the "Front" sweeps in a long arc northeastward, forms the northern boundary of the principal Anthracite Fields, and eventually passes eastward into New York by way of the Delaware River Valley. The Allegheny Plateau breaks off abruptly at the Lackawanna Basin. This long, narrow, coal-measure-filled syncline separates the larger plateau from the lesser Pocono Plateau to the east. The Pocono Plateau resembles physiographically and geologically the Allegheny Plateau but is of much smaller extent, confined between the Anthracite Fields and a great bend in the Delaware River. Yet, despite their similarity, it is doubtful if these plateaus were ever continuous across the region of the Lackawanna Basin.

STRUCTURES AND STRATA

The rocks which crop out on the Allegheny Plateau belong to the Devonian, Mississippian, Pennsylvanian, and Permian systems. The Pocono

Plateau is capped chiefly by Devonian strata with a little Mississippian along its northern and western margins.[2] In general, the bedding is nearly horizontal, but the uniform structure of the Allegheny Plateau is interrupted by shallow synclines and gentle anticlines which are similar in trend to the Appalachian Mountain structures of much greater plunging synclines of the neighboring Anthracite Fields, and along the northern border adjacent to the Lackawanna Basin, where they dip abruptly under that structure (see Fig. 2).

The Lackawanna Basin as stated is an isolated bit of intense Appalachian type of folding. It is a structural anomaly in that it was developed between the two

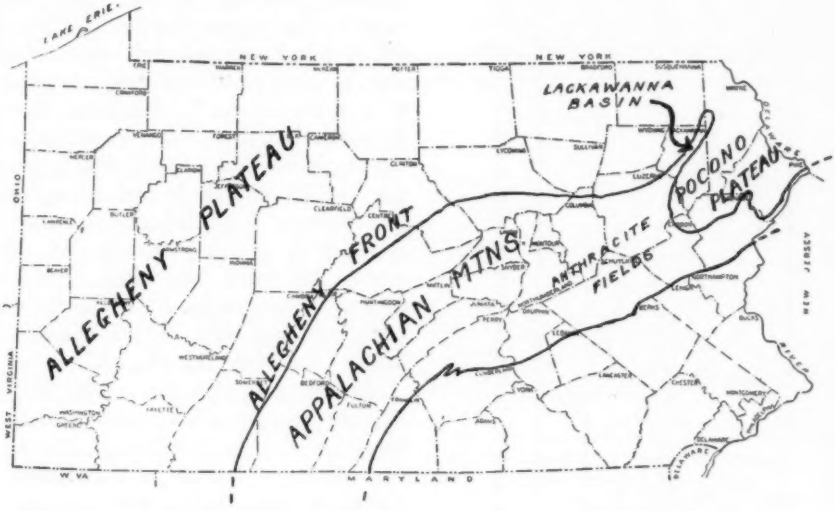

FIG. 1.—Outline map of Pennsylvania showing the location of the Lackawanna Basin and its relations to the major physiographic features of the state.

amplitude to the east. This relation is significant because it helps to set off structurally the plateau synclines from the Lackawanna Basin. The formations of the Pocono Plateau dip very gently and uniformly northwestward except along the western border of the upland, where the beds are thrown into crenulations across the ends of the westward-plateaus, and its intensity is quite unlike the shallow synclines of the Allegheny Plateau, nor is it aligned with the neighboring Appalachian structural trends. To understand these peculiarities, it is necessary to summarize the local Devonian and Mississippian stratigraphy.

The Devonian of the Pocono Plateau, as of most of northeastern Pennsylvania, is essentially confined to the thick Catskill continental facies.[3] The succession is:

[2] Anomalously, the Pocono Plateau was for years assumed to be the type locality of the Pocono formation due to a long-standing confusion of that unit with the Honesdale sandstone of the Devonian. Cf. Bradford Willard, *Pa. Topog. and Geol. Surv. Bull. G19* (1939), p. 304.

[3] *Ibid.*, chap. viii: "The Devonian of Pennsylvania."

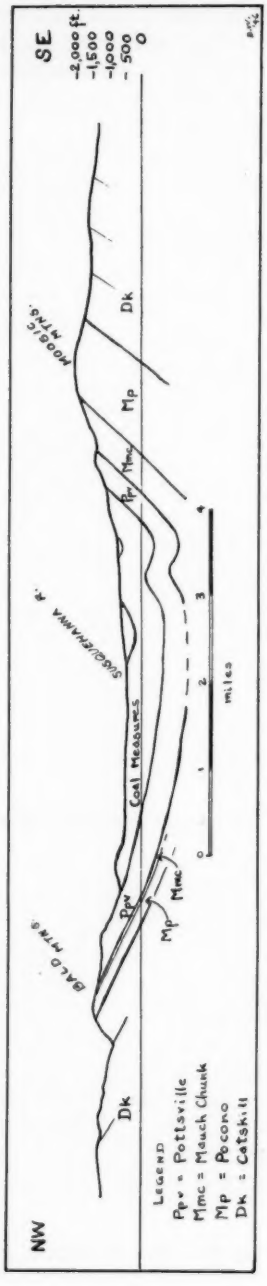

FIG. 2.—Somewhat generalized northwest by southeast section across the Lackawanna Basin in the vicinity of Wilkes-Barre

Mount Pleasant red shale
Elk Mountain sandstone
Cherry Ridge red shale
Honesdale sandstone
Damascus red shale
Shohola sandstone and shale

This whole succession of alternating red and nonred units closely resembles in lithology the overlying Mississippian. Despite heavy glaciation across the Plateau, outcrops indicate that over most of the upland the Catskill is distributed in a succession of broad northeast- to southwest-trending bands roughly parallel to the Lackawanna Basin. Successively older units crop out toward the southeast. The Catskill dips beneath the Lackawanna Basin and emerges on its northern flank, whence, westward, most of it passes gradually into the marine Devonian formations of north-central Pennsylvania. Throughout there is a gradual, uniform thinning from the Plateau westward (cf. Fig. 2).

The Mississippian formations of the Plateau are a simplified repetition or continuation of Catskill lithology. The system consists of two major units: Mauch Chunk red shale and Pocono sandstone and conglomerate.

The Mississippian in northeastern Pennsylvania is well exposed along the northern and western borders of the Pocono Plateau. It supports the Moosic Mountains, which separate the plateau from the basin, and it occupies the troughs of westward-plunging synclines in the Anthracite Fields west of the plateau. The Mississippian beds, like the Catskill, dive under the Lackawanna Basin. Similarly, they emerge along its farther side. Here, however, the analogy with the Devonian lessens. The Mauch Chunk, instead of passing into a marine facies, pinches out completely with no hint of salt-water conditions and but little litho-

logic change. The Pocono formation also thins but does not completely vanish. After the manner of the Devonian, its attenuated remnant merges with the marine Mississippian of north-central Pennsylvania.[4]

The decrease in thickness of the Mississippian system takes place chiefly in an astonishingly short distance beneath the Lackawanna Basin (Figs. 2 and 3). In the Moosic Mountains opposite the middle and southern parts of the basin, it attains a thickness of some 3,000 feet. Along the western border opposite, the system reappears with a thickness of only 300–500 feet. This remarkable change has taken place in a linear distance of only 6 or 8 miles.

That the Mississippian once spread across the Pocono Plateau is inferred from its abrupt eastern termination in the face of the Moosic Mountains and from its thickness under the coal measures to the west of the plateau. Further support of this supposition is had from additional observations and deductions based upon marine-continental relations in Pennsylvania during most of the Paleozoic. This has been discussed in an earlier article.

Throughout the Paleozoic there have been in Pennsylvania recurrences of continental facies tending repeatedly to displace their marine contemporaries. The recurrence may be more or less cyclic. These displacements have been referred to as continental to marine facies shifts. Actually, the freshwater beds themselves display two marked cumulative changes independent of their displacement of the marine beds. First, there is a progressive, chronological evolution from red to non-red rock color. . . . . Second, there is a progressive shift in position or westward and northwestward spreading at each recurrence of continental beds. . . . . Each successive continental facies . . . . spreads farther west or northwest than did its predecessor. In each there is a progressively greater encroachment of freshwater strata upon the Appalachian geosynclinal seaway.[5]

In addition to the above, the maximum thickness of the several continental facies of the systems migrated westward or northwestward. In the Silurian, maximum continental deposition appears to have occurred in northern New Jersey. In Devonian times the thickest Catskill was laid down in the region of the Upper

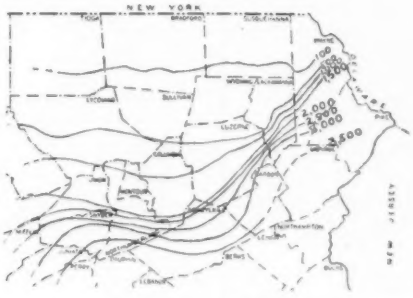

FIG. 3.—Isopach map of the Mississippian system in northern Pennsylvania, based principally upon field work by the author.

Delaware Valley. The maximum of Mississippian fresh-water beds probably occupied the present region of the Pocono Plateau. Finally, the thickest Pennsylvanian deposition took place in the Anthracite Fields. Such a shift may be attributed to progressive uplift of the general region to the east and southeast from which sediments were derived, causing erosion and partial re-working of the more remote, older beds whose debris was incorporated into newer formations to the west and northwest. This movement might be termed a

[4] For a full account of this change see Bradford Willard, "Continental-Marine Mississippian Relations in Northern Pennsylvania," *Bull. Geol. Soc. Amer.* (in press), and abstract in "Proceedings" of 1945 meeting.

[5] Bradford Willard, "Recurrent Paleozoic Continental Facies in Pennsylvania," *New York Acad. Sci., Annals*, Vol. XL, Art. 4 (1940), p. 284.

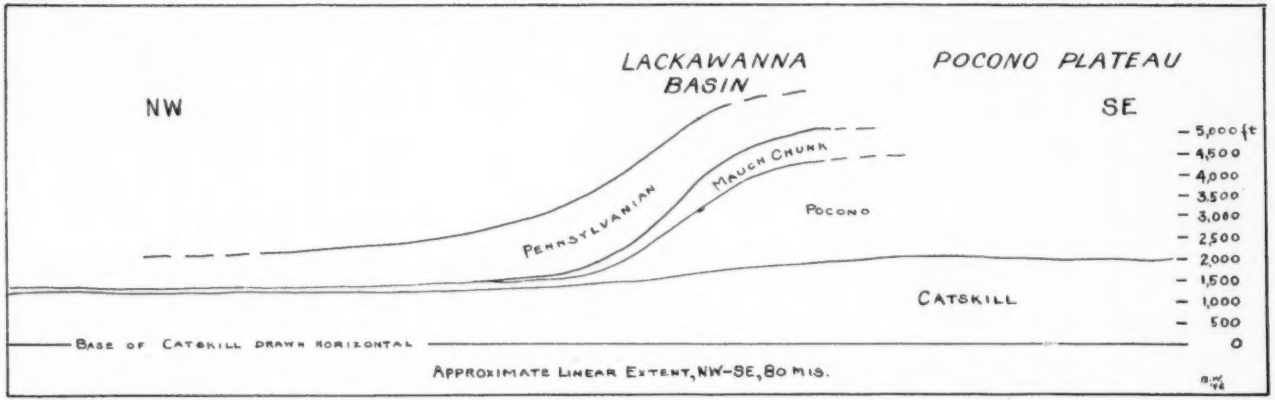

FIG. 4.—Restoration of northwest by southeast section through the regions of the Lackwanna Basin and the Pocono Plateau toward the close of Paleozoic time. Note the horizontal position of the basal Catskill. Presumably, from its present position, comparatively little isostatic adjustment affected the continental formations here involved.

migration of the geanticline rather than a migration of the geosyncline. If so, the Mississippian probably reached its maximum thickness in the region of the plateau, east of which its distribution was quite limited.

HISTORY

If we reconstruct late Paleozoic conditions in northeastern Pennsylvania, we find that the continental Devonian is overlain by continental Mississippian and this in turn by the fresh-water–formed Pennsylvanian. Presumably, all three systems extended east of their present boundaries, but, as suggested, the maximum Mississippian sedimentation probably occurred in the Pocono Plateau region. The reconstructed section is shown in Figure 4. Note the regular, progressive thinning of the Devonian and the abrupt change in thickness of the Mississippian. This abrupt change coincided with the region today marked by the synclinal Lackawanna Basin. Such a change in thickness might be a potential line of structural weakness.

When the Appalachian Revolution set in, the Paleozoic formations of northeastern Pennsylvania were pushed northwestward. Formations well to the east, presumably terminating in the thinning Devonian, crumpled; but in the region of the Pocono Plateau, the heavy, thick Catskill and even thicker Mississippian and perhaps some coal measures formed a competent bastion. Instead of folding, it transmitted the thrust. But, at the line of thinning of the Mississippian, downbuckling took place to form the Lackawanna Basin. Subsequent uplift and erosion cleared the Pocono Plateau of all but remnants of the Mississippian and exposed the Devonian beds, but the downwarping preserved the Mississippian and Pennsylvanian of the basin.

ORIGIN OF CERTAIN WIND GAPS IN THE LARAMIE MOUNTAINS, WYOMING

D. L. BLACKSTONE, JR.
University of Missouri

ABSTRACT

Wind gaps in the Laramie Mountains, Wyoming, are described. The wind gaps are due to superposition of streams upon the pre-Oligocene topography and later capture by headward eroding tributaries. The tributaries are able to extend their valleys headward more rapidly than the main stream because of the soft Tertiary sediments in which they head.

INTRODUCTION

The Laramie Mountains of Wyoming are the northern structural and topographic continuation of the Front Ranges of Colorado and are included by N. M. Fenneman[1] in the Southern Rocky Mountain Province. The principal geologic features of the range, and the wind gaps described, may be located on the index map (Fig. 1). The range in broad outline is an asymmetric anticline, with a steep eastern limb and a gently dipping western limb. The basic pattern is modified by thrusting and transverse faulting and local folds of reverse asymmetry, as well as folds which trend transverse to the principal northwest-southeast axis of the uplift. The sedimentary sequence ranges from Mississippian (?) to late Tertiary and is adequately described by N. H. Darton,[2] hence is not presented here in detail. The physiographic features of the Laramie Mountains were first described by Eliot Blackwelder[3] and have been further discussed by T. S. Lovering,[4] F. M. Van Tuyl and Lovering,[5] J. L. Rich,[6] and C. J. Hares.[7]

The Laramie Range came into existence during the Laramide revolution. The Cretaceous Lance and Paleocene Fort Union formations were deformed and later unconformably overlain by the Eocene Wasatch in the Powder River Basin, northeast of the Laramie Mountains. The Wasatch formation was later deformed and the mountains eroded deeply, so that a drainage pattern developed, moderately well adjusted to rock structure. It is possible that a part of this erosion took place in the late Eocene and continued into the early Oligocene. Resistant rock units were expressed as hogbacks or as topographic prominences.

Oligocene and Miocene sediments were deposited by aggrading streams in the pre-Oligocene valleys. The older topog-

[1] *Physiography of Western United States* (New York: McGraw-Hill Book Co., 1931).

[2] Laramie-Sherman Folio, *Geologic Atlas of the United States*, No. 173 (1910).

[3] "Cenozoic History of the Laramie Region, Wyoming," *Jour. Geol.*, Vol. XVII (1909), pp. 429–44.

[4] "Geologic History of the Front Range, Colorado," *Proc. Colo. Sci. Soc.*, Vol. XII, No. 4 (1929), pp. 59–111.

[5] "Physiographic Development of the Front Range," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1291–1350.

[6] Discussion of Lovering and Van Tuyl papers, *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 2046–51.

[7] "Deeply Weathered Pre-Cambrian Peneplain a Basic Factor in the Genesis of the Sherman Flat Surface, Laramie Mts., Wyoming," *Proc. Geol. Soc. Amer.* (1934), p. 81. (Abstract.)

raphy on the margin of the mountains was buried, and in places Tertiary sediments extended across the crystalline core of the range (see Fig. 1). The maximum height of the Tertiary flood-plain surface is not known. It was high enough, however, to allow extensive overlap of Tertiary materials onto the pre-Cambrian crystalline core of the mountain mass. The Tertiary section of this area includes the White River group, composed of the Chadron and Brule formations and the Miocene Arikaree group, as defined by A. L. Lugn[8] in western Nebraska.

The region was excavated in post-Miocene time, and much of the Tertiary

[8] "Classification of the Tertiary System in Nebraska," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1245–76.

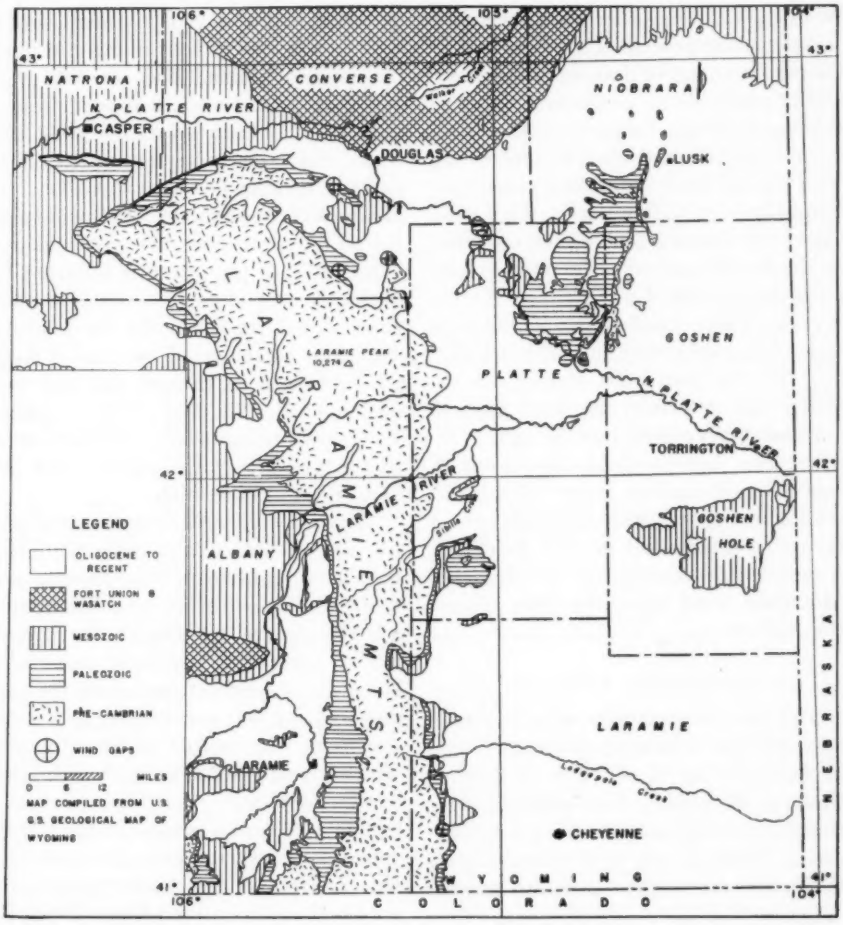

FIG. 1.—Index map of a portion of Wyoming, indicating the regional geology and the location of observed wind gaps.

sediment has been removed. In this excavation the drainage pattern of streams that previously flowed on the depositional surface of the Tertiary sediments has been in part superposed on older strata. The major streams were superposed over major structural features, as illustrated by the course of the North Platte River across the Hartville uplift in eastern Wyoming. Minor streams show equal disregard for structure in many cases. Wind gaps and meander scars developed and are in the process of development in the readjustment of drainage that is still taking place. Some consequent streams developed, as the Tertiary cover was removed, and are adjusted to underlying structure on both sedimentary and pre-Cambrian crystalline rocks. The wind gaps to be described have been observed on the ground and on aerial photographs prepared for the United States Forest Service. These wind gaps are due to a type of stream piracy in which a tributary pirates the main stream. R. S. Sharp[9] has described the wind gaps in northwest Wyoming due to piracy by tributaries but without superposition from unconformable cover. Headward erosion by the tributaries depends upon a favorable differential in rock hardness. A detailed description of the Laramie Mountain wind gaps and their formation follows.

DEERE CREEK WIND GAP

The most conspicuous wind gap seen by the writer is located on Deere Creek, in Sec. 7, T. 29 N., R. 72 W., Converse County, Wyoming. The geologic relationships in this area are shown on Figure 2. Deere Creek and its tributaries head either on the pre-Cambrian crystalline rocks or on the unconformable Tertiary cover. The general northeast trend of the stream is influenced by a pronounced N. 35° E. strike in the structure of the pre-Cambrian rocks. Deere Creek is superposed across a sharply folded anticline in T. 30 N., R. 71 W., as it flows from the wind gap to the North Platte River.

At the Deere Creek locality the Pennsylvanian Hartville limestones strike N. 70° W., and dip 12° N.E. to form a southwest-facing escarpment along the flank of the mountains. The present gross topography is a broad, shallow, exhumed valley, cut in both crystalline pre-Cambrian and later sedimentary strata. In this broad valley lie remnants of Tertiary White River sediments. The wind gap lies on the south side of Deere Creek and is incised in a pink granite intruded by basic dikes. The gap, in part, parallels the strike of the dikes and the jointing. The floor of the wind gap has a steep gradient, and at present the east end does not enter the main valley at grade. The walls are essentially vertical owing to the jointing in the granite, and are more than 150 feet high.

While Deere Creek occupied this gap, the rate of downcutting in the section of the channel upstream from the gap was retarded, because of the establishment of a local baselevel upstream from the barrier of crystalline pre-Cambrian rocks. Immediately downstream from the gap, downcutting was accelerated because of the relatively softer sediments over which the stream flowed in the filled pre-Tertiary valley.

The accelerated erosion in the stream course downstream from the gap likewise accelerated the downcutting in the tributaries that entered Deere Creek below the gap. One of these tributaries eroded headward in the Tertiary fill in a

[9] "Superposed Windgaps of Cedar Mountain, Wyoming," *Jour. Geomorph.*, Vol. IV (1941), pp. 325–27.

position parallel to the gap and also approximately parallel to the axis of the pre-Tertiary valley. The tributary, advantageously situated on the Tertiary fill, was able to erode a channel to a lower elevation than the portion of Deere Creek above the gap. The tributary eroded headward until it captured the master-stream, causing it to abandon the incised gorge in the granite that is now the Deere Creek wind gap.

The new channel of Deere Creek, located on the Tertiary fill, was rapidly deepened until granite was again exposed. The stream incised a second gorge in the granite and has continued to occupy it because the excavation of the pre-Oligocene valley is essentially complete at this point. No tributary is able to cut rapidly headward at the expense of the master-stream and effect a capture unless there is a marked differential in resistance to erosion due to softer strata in part of the course.

The establishment of the channel of the stream at the Deere Creek wind gap may have taken place in one of two ways. First, the stream may be considered to have been superposed on the granite, as described above. This interpretation depends on the height on the mountain flanks to which the Tertiary fill reached before excavation began.

A second possibility is that the position of the gap is approximately at the point of a previous contact between the granite and the Tertiary fill. In this case Deere Creek may have been flowing in a

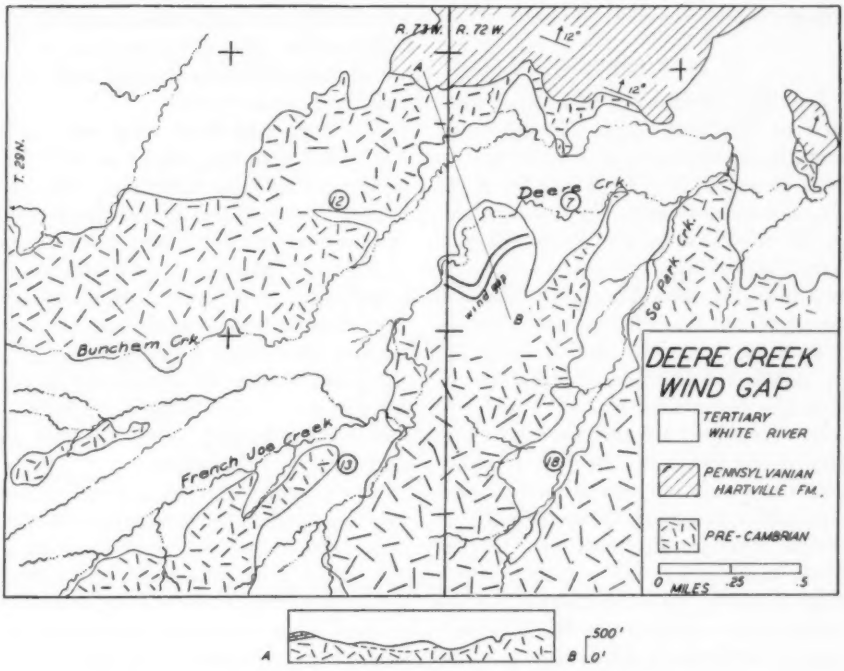

FIG. 2.—Geologic map and cross section of the Deere Creek wind gap

structurally controlled channel to a point at the lower end of the gap, where it debouched upon the Tertiary fill. The capture that caused the wind gap took place, then, by a tributary flowing on the fill under more favorable conditions for channel deepening.

The evidence from localities described below lends support to the first interpretation.

TRAIL CREEK

Excellent examples of small-scale wind gaps or meander scars were observed near the headwaters of a tributary to Trail Creek, in Sec. 26, T. 30 N., R. 71 W., Converse County, Wyoming (Fig. 3). At this locality the Pennsylvanian Hartville formation is exposed in a northwest-plunging fold. The axis of the fold trends N. 20° W., and the strata on the west flank strike N. 40° E. and dip 23° N.W. This fold extends northward from the mountains and is unconformably overlapped by the fine clays and silts of the Oligocene Brule (?) formation. Pre-Cambrian crystalline rocks are exposed 2 miles south of the map area in normal stratigraphic position. The pre-Brule topography was a rather broad, north-trending valley, excavated in some of the softer strata of the Hartville formation. Trail Creek established a northward-flowing position toward the master-drainage of the North Platte River and, together with its tributaries, began to excavate the immediate area. The tributary of Trail Creek under consideration (in Sec. 26) eroded down to the hard dolomitic limestones of the Hartville formation. When this formation was exposed, the small intermittent stream (at least, so it is now) incised portions of three meanders into the more resistant Hartville formation.

The Tertiary strata west of the incised meanders are thicker because of the relationship of the westward-dipping contact between the Hartville formation and the Tertiary. The tributaries eroded headward, in courses parallel to, and west of, the main stream. The tributaries thus lowered their channels (see cross section, Fig. 3) and captured the main stream in such a manner as to isolate the meanders, which were incised in the Hartville formation. The abandoned portions of the stream course remain as small-scale wind gaps or meander scars.

The largest of these wind gaps (*a* in Fig. 3) is $\frac{1}{8}$ mile long, about 40 feet deep, and 25–30 feet wide at the floor. This gap is now about 50 feet above the present stream channel. Two shorter wind gaps (*b* and *c* in Fig. 3) occur to the south (upstream), at elevations which suggest that they represent portions of one continuous channel at a particular stage in the downcutting. The gradient obtained by connecting the floors of channels *a* and *b* is moderately steep but was not determined by instrument.

The channel marked *c* (Fig. 3) and now occupied by the stream has the same characteristics as the meander scars at *a*, *b*, and *d*. The stream occupies a channel 15 feet deep, 200 feet long, and about 10 feet wide, incised in limestone. Immediately upstream and downstream from the incised channel, the stream is at present eroding a channel in soft Tertiary fill. A minor intermittent tributary is eroding headward in such a fashion that a very narrow, low divide exists between the major and the minor streams. Capture is imminent. When capture takes place, *c* will be isolated as a meander scar similar to those mentioned above.

The method by which the capture took place is well illustrated at the Trail Creek locality. A repetition of capture occurred, so that a second meander scar

developed on the same exhumed slope, but at a lower elevation. Apparently, the stream in a part of its course incised a new channel (*d*) in the limestones and dolomites, while the upper reaches continued to occupy the previously cut notch (*c*). The two sets of wind gaps thus give a measure of the effect on down-cutting caused by the disturbance of local baselevel.

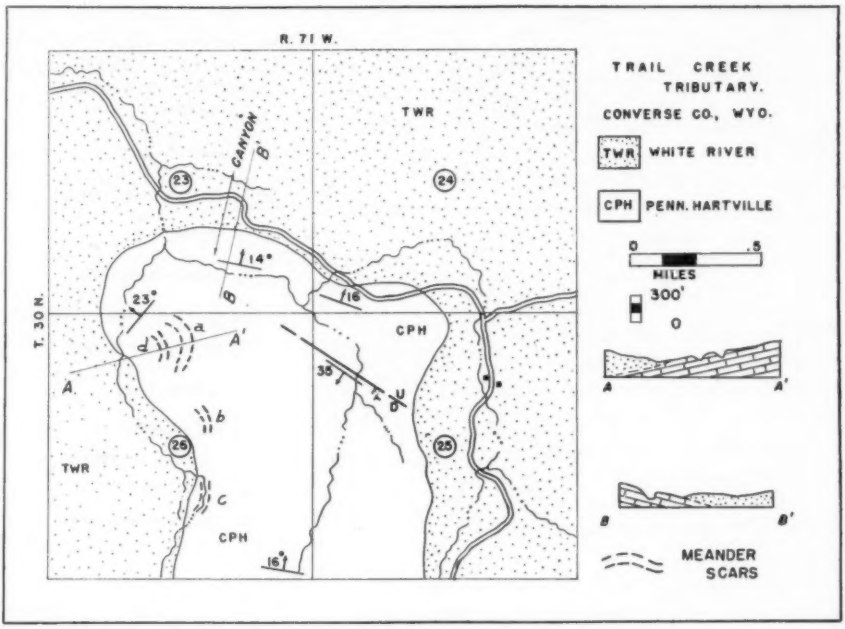

FIG. 3.—Geologic map and cross section of the Trail Creek tributary area, with location of wind gaps

Superposition of a stream upon the Hartville group of rocks in the S.E. $\frac{1}{4}$ of Section 23 (Fig. 3) has set up the conditions necessary for a potential capture in the same vicinity. A canyon has been eroded into limestones and dolomites that dip 14° northeast. The gorge is 40–60 feet wide at the floor and over 100 feet in depth. The stream has shown some tendency to migrate down dip along the bedding planes of the resistant strata, with a resulting overhang of the cliff on the down-dip (north) side of the gorge. The stream flows over Tertiary strata both upstream and downstream from the canyon. Sand and gravel derived from conglomerate lenses in the Tertiary sediments upstream serve as tools by which the stream rapidly erodes the limestones and dolomites.

A tributary heading eastward from the center of Section 23 is separated from the main stream by a low divide near the boundary line between Sections 23 and 24. In this case it is possible that the major stream, because of the clastic materials available to it and its greater volume of water, may be able to lower the main channel in hard rocks faster than the tributary, eroding headward in soft

material, can shift the divide. The conditions are potentially suitable for capture, and abandonment of the major channel will form a wind gap.

BED TICK CREEK

This locality is in Secs. 31 and 32, T. 32 N., R. 72 W., Converse County, Wyoming, at the headwaters of Bed Tick Creek (Fig. 4). One of the thickest sections of White River strata in the region is here exposed along the north side of the valley. The present drainage is roughly parallel to the north flank of the exhumed La Bonte anticline. The elevation of the exposed crystalline core of this anticline is 1,400 feet higher than the surrounding country. The Tertiary White River sediments overlap steeply dipping hogbacks of Paleozoic and Mesozoic rocks on both the southwest and the northeast limbs of the fold. At the head of Bed Tick Creek the stream gradient steepens rapidly, where the streams are actively cutting headward (west) and creating an erosional scarp upon the White River sediments. The main channel of the stream has been superposed upon the Hartville formation in three places, through which it has cut canyons, approximately 100 feet deep, $\frac{1}{8}$ mile long, and some 50 feet wide at the bottom. The existing canyons have not been isolated to form wind gaps or meander scars, but the condition has almost been attained in two cases.

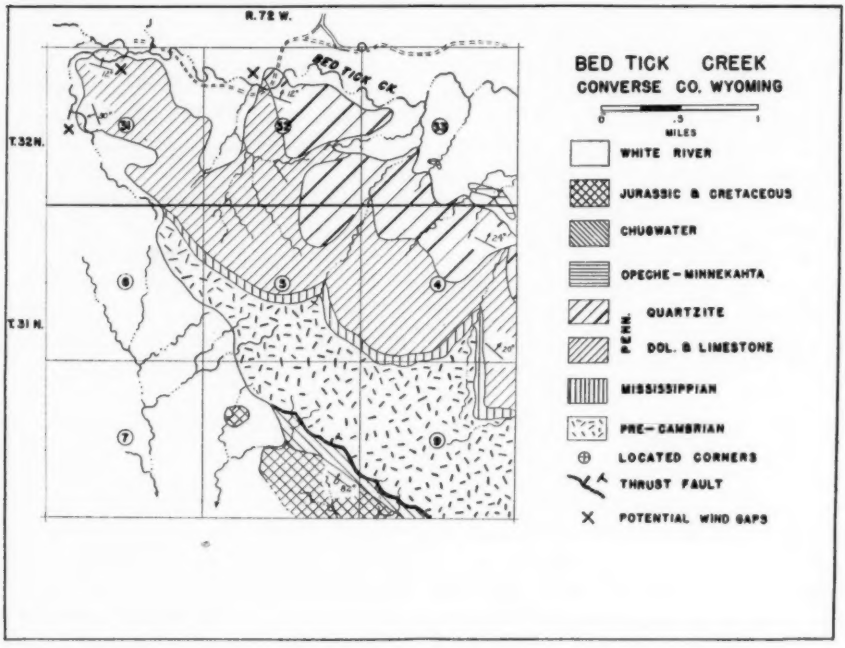

FIG. 4.—Geologic map of the Bed Tick Creek area and location of potential windgaps

The middle canyon (N.E.-N.W. Sec. 31, T. 32 N., R. 72 W.) is most nearly

isolated. On the north rim of the canyon the observer may stand upon soft Brule clay and look directly south into the incised channel cut into the dolomite of the Hartville formation. Immediately to the north, the observer may look into a narrow, steep-sided gully, eroded in the fine-textured clays and silts of the Brule formation. This tributary gully now heads within approximately 300 feet of the main stream, and the elevation of the tributary channel is essentially that of the gorge in the Hartville dolomite. Bed Tick Creek above the gorge swings to the south and southeast in a broad semicircle, and at a distance of approximately $\frac{1}{2}$ mile south it occupies a smaller incised notch.

The tributary drainage heads to the west and is not at present paralleling the master-stream but tends to diverge at an angle. The actual capture will probably be accomplished by a minor tributary.

LARAMIE-SHERMAN FOLIO, WYOMING

An examination of the Laramie-Sherman Folio, *Geologic Atlas of the United States*, No. 173, has revealed another potential wind gap in the process of development. This locality has not been visited in the field but was studied from the topographic and geologic maps and appears to be similar to those already described in detail. The locality is near the corner common to T.'s 13 and 14 N., and R.'s 69 and 70 W., Wyoming. A fork of Crow Creek, unnamed upon the topographic map, flows across this area. The stream heads on the Sherman granite and flows eastward across granite, gneiss, and schist and then across a small area of Oligocene Brule formation, before resuming its course over gneiss and schist finally to reach the plains along the east side of the mountains. The portion of the course between the two Tertiary exposures is in a moderately deep valley cut into the metamorphic rocks.

An intermittent tributary, which enters the Middle Fork of Crow Creek in Sec. 21, T. 14 N., R. 69 W., is eroding headward across Tertiary sediments and, if the fill is deep enough, will eventually capture the unnamed fork of Crow Creek. In this case the capture would be effected not by a tributary of the master-stream itself but by a parallel drainage and would entail a greater readjustment of drainage.

CONCLUSIONS

The described wind gaps are due to drainage changes in a superposed drainage pattern by headward erosion in the unconformable cover. Moderate to strong relief in the topography preceding the deposition of the cover has aided in the process of drainage rearrangement.

The position of the highest wind gaps is a measure of the depth of fill deposited by the late Tertiary streams. A study of the character of the unconformable late Tertiary sediments indicates that much of the material was not locally derived and was laid down as a widespread alluvial deposit.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge the field assistance of John Webb and the support of the Geology Department of the University of Missouri in the purchase of aerial photographs.

BISON-POLISHED BOULDERS ON THE ALBERTAN GREAT PLAINS

J HARLEN BRETZ
University of Chicago

During a nine-thousand-mile traverse of the drift-covered plains of southern and central Alberta and adjacent Saskatchewan, the writer saw several dozen glacial boulders which carried more or less complete bands of polish on vertical and near-vertical sides, the polish limited to projections—nowhere occurring in the pits, pockets, or indentations of the boulder's surface. None of these boulders was polished on the top or on gentle upper slopes. Limestone boulders carried almost as good a polish as those of quartzite. On granite boulders there was no difference in degree of polish on adjacent quartz and silicate grains.

Boulders less than about five feet in diameter do not possess the polish. Up to perhaps fifteen or twenty feet in diameter, polish-bearing boulders all are surrounded by a moat, an encircling depression in the drift. Still larger boulders have no moat or have a very weakly developed one. No polished surfaces are more than five or six feet above the immediately adjacent ground surface. On those without the surrounding moat the belt is limited to a width of two or three feet—rarely extends down to the ground.

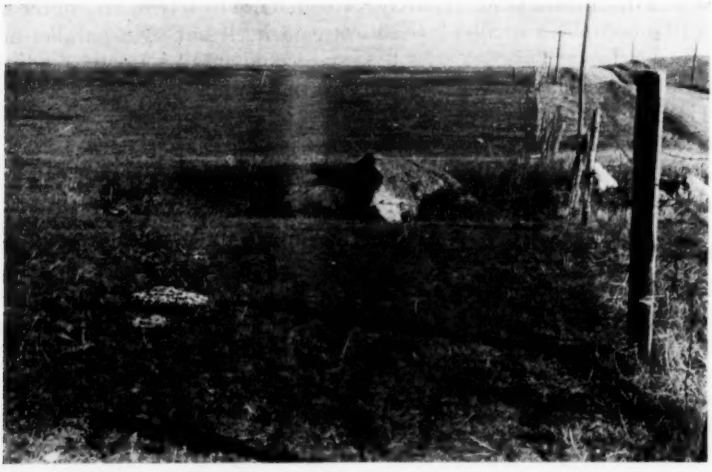

FIG. 1.—Granitic erratic boulder with polished edges, down in a basin whose outer part constitutes a moat which has been shallowed subsequently by wash. South of Macklin, Saskatchewan.

The theory embodied in the title of this paper explains the moat as a result of the trampling of generations of bison, breaking the grass cover while rubbing against the boulder. Wind blew away some of the bare soil, and, when the

FIG. 2.—Limestone erratic boulder, with polished edges. Crawling Valley, north of Bassano, Alberta. Tall grass somewhat obscures the moat. Photo by Paul Herbert.

FIG. 3.—Gigantic quartzite erratic boulders near Black Diamond, Alberta. Inconspicuous development of moat. Polish limited to lower 4 or 5 feet of sides of boulders.

ground was wet, bison carried mud away between their cloven hoofs.

The theory must also explain the fact that if these moats were refilled today many boulders would project so little above the drift that no rubbing-place would be provided. An additional item is therefore needed. It is as follows:

Much bentonitic material has been incorporated in the Albertan plains drift from underlying Cretaceous and Eocene shales, and this clay till, when wet, is extremely slippery. A special zigzag steering technique is needed to keep the rear wheels of a car from slipping off the low crown of a recently scraped earthen road surface wet after a brief rain. This same lubrication of wetted till, where an incipient moat has collected water and caused saturation beneath the boulder, has allowed the mud to be slowly squeezed out by the weight of the boulder, later to be tracked away as such or blown away when dry. Thus the moats have been deepened and the boulders have continued to settle until the tops of some are down to the level of the surrounding till surface.

Very large boulders roofed over and protected the underlying till surface from this softening procedure, hence have settled very little, if at all, and possess only a suggestion of the moat.

The character of the polish and the pattern of its distribution is convincing evidence that neither glacial nor wind abrasion is responsible. Mudflow polish on these boulders is nearly as improbable as gastrolith polish. The recency of action is indicated by the freshness of the gloss on the limestone boulders.

Although domestic cattle now use some of these boulders for rubbing-places, it seems impossible that the degree of polish and the depth of moat could have been produced by them in the few decades since the bison disappeared. The road and fence shown in Figure 1 came with settlement of Macklin, Saskatchewan, and with the introduction of cattle. The moat obviously was already there.

REVIEWS

Den sista nordiska nedisningens förlopp ("History of the Last Nordic Glaciation"). By ERIK LJUNGNER. (*Geol. Fören. Förhandl.*, Vol. LXVII.) Stockholm, 1945. Pp. 225–40.

This study is largely based on a chronological separation of the *roches moutonnées*, or glaciated knobs, in Swedish Lapland at about 17° E. and the Polar Circle. Hardness, location, and orientation of the knobs have been specially considered (p. 226). Contrary to general belief, striae formed during the earliest stages of the latest glaciation may be preserved where the conditions have been favorable. From knobs and scratches Dr. Ljungner has deduced several successive directions of the ice movements in the Scandinavian mountain range, which he names the "Scandes."

In the region studied there seem to be striae from five main directions, in chronological order from the northwest (*a*), the southeast (*b*), the east (*c*), the northwest (*d*), and the southwest (*e*) (p. 228). The oldest northwest striae and glaciated knobs are referred to Stage I of the glaciation of the Scandes. The ice was limited to the range but was thick and may have had a divide, which, part of the time, lay west of the watershed. From this time there are cirques on the east side of the mountains, suggesting by their elevations that the glaciation line lay 1,100–1,200 meters lower than at present (p. 230).

The southeast striae (*b*) in the Scandes are associated with the position of the ice divide at the Gulf of Bothnia during the maximum extent of the ice, Stage II. The greatest observed amount of glacial depression (or later uplift) of the earth's crust, 295 meters, is to be found on the Swedish coast near lat. 63° N.; but it seems probable that the site of the actual center of ice accumulation and of maximum crustal depression was considerably farther south (p. 233). The ice sheet may have culminated at separate times on the Atlantic and in the south and southeast. On the east slope of the Scandes the ice surface attained much greater altitude during this stage than during Stage I. Oscillations in the southern marginal belt of the large ice sheet would not be recorded in the Scandes and are not discussed by Ljungner.

A shift in the direction of the striae from the southeast to the east (*c*) indicates a northward migration of the ice center during a late stage of deglaciation, Stage III (p. 235). Still later the ice divide lay north of the area studied, on the east slope of the range, and the ice dammed up lakes on its west side.

During Stage I, precipitation and winds may have been about as today, but the temperature was lower (p. 236). The transition from Stage I to Stage II is not well understood, since the accumulation of ice on the range tended to sharpen the continentality of the lowland to the east and to favor foehn winds (p. 237). Winds, precipitation, and Gulf Stream are thought to have resembled those of today until the lowland was covered by ice. When the general temperature-lowering had shortened the melt-season so that part of the winter's snow persisted until the next winter, the greatly increased reflection of the solar heat by the snow may have further lowered the temperature, so that the permanent snow fields grew and the glaciation line sank. Piedmont glaciers then pushed over the lowland and formed the nucleus of the ice sheet. The origin of the snow is not discussed by Ljungner; but, if the snow was partly, perhaps largely, wind-drifted from the west side of the divide and partly locally precipitated, Ljungner's explanation of the transition does not differ much from those previously applied to the ices in Scandinavia and western Canada. Before long, an anticyclone formed over the ice and snow and grew in strength. The cyclone tracks over southernmost Scandinavia gained in importance at the expense of those over the northwestern part of the peninsula, and snow was precipitated on the Fenno-Scandian lowland, which was quickly flooded by ice (p. 238). The ice sheet grew to attain its maximum.

Since the most favorable temperature for snowfall is 32° F., a temperature-lowering causes the optimal zone of snowfall to move toward the Equator and downward in the mountains. Thus temperature-lowering was one cause for the southward spread of the ice. Another cause was the development of the anticyclone and the southward move of the cyclone tracks.

During the deglaciation, the ice center or ice axis shifted northwestward. Shortly before the end, the ice divide moved toward the Scandine watershed because the melting was asymmetrical, because the ice divide must be higher than the ice on either side, and because high-latitudinal cyclones grew in frequency and importance (p. 239). But, on account of a rapid temperature rise, the ice shed never reached the crest of the range, and the local glaciers were too insignificant to supply sufficient nourishment to the shrinking ice remnant.

The reviewer wishes to call attention to the analogy between the Nordic ice sheet and the Cordilleran-Keewatin ice of northwestern North America. Each started in a mountain range lying athwart the cyclonic paths on the west side of a continent. How the ice spread to the plains on the lee side and there accumulated to a huge ice sheet has not been adequately explained in either case. However, that the European ice sheet originated in the Scandes is obvious, for there was no other possible starting-point. That the Keewatin ice grew from the Canadian Cordillera and its ice is probable enough.

The Wisconsin glaciation had two separate maxima in western North America—the Iowan and the Mankato. The last Nordic glaciation also had widely spaced maxima, according to German geologists. Since the interval between the solar-radiation maximum, about 128,000 years ago, and the minimum, 116,000 years ago, may have been too short to permit the formation of a huge ice sheet, Würm 1 of the Germans may, at most, have been a mountain glaciation. Perhaps the glaciation of the Scandes was the correlative of Würm 1. Perhaps also the Warthe and the Weichsel continental glaciations were correlatives of the Würm 2 and Würm 3 and of the Iowan and the Mankato. The border of the Warthe glaciation runs west of Hamburg, north of Breslau, south of Warsaw and Minsk, through Moscow, and northeastward into Siberia (for Russia see R. F. Flint and H. G. Dorsey, "Glaciation of Siberia," *Bull. Geol. Soc. Amer.*, Vol. LVI [1945], pp. 89–106; Pl. I, "Latest Glacial Stage"). The border of the Weichsel runs east of Hamburg, south of Berlin and Posen, and in a bow through Russia and the Kanin Peninsula to Barents Sea.

A late paper by Ljungner ("Ein ostskandinavisches Vergletscherungsintervall," *Geol. Fören. Förhandl.*, Vol. LXVIII [Stockholm, 1946], pp. 81–86) makes it clear that the above-mentioned mountain glaciation, Stage I, which was of very long duration, immediately preceded the continental glaciation. But, separated from Stage I by an ice-free interstadial, there now seems to have been another, still older, glaciation, which then might be the correlative of Würm 1.

The comparison may be carried further. The greatest glaciation in northeastern Siberia (the latest one is not mapped but was small), as described and mapped by Flint and Dorsey (also G. B. Cressey, "Glaciation in Siberia," *Geog. Rev.*, January, 1946, pp. 159–60), may have resembled early stages of Labrador ices. Much or most of the moisture in northeastern Siberia came from the Sea of Okhotsk and the Bering Sea. Cyclonic storms from the distant Atlantic brought too little precipitation to permit the growth of a large ice sheet. Since storms could bring little if any moisture across a large Nordic ice sheet, the glaciations in Siberia are by some Russian geologists believed not to have been synchronous with the Nordic glaciations (Flint and Dorsey, p. 103). The last Labrador glaciation is held by the reviewer to have started rather late by moisture from the east and to have culminated in the interval between the Iowan and the Mankato maxima (*Amer. Jour. Sci.*, Vol. CCXLIII *A* [1945], pp. 1–39).

ERNST ANTEVS

Some Glaciomorphological Forms and Their Evidence as to the Downwasting of the Inland Ice in Swedish and Norwegian Mountain Terrain. (Swedish with English summary). By CARL M:SON MANNERFELT. (*Geografiska Annaler.*) Stockholm, 1945. Pp. 1–239; pls. 15.

This beautifully illustrated memoir is, first, a study of the erosional and depositional land forms which arose during the waning of the last remnants of the latest ice sheet in central Scandinavia, about 10°–14° E. and 62°–63° N. It is, furthermore, a study of the mode of the ice wasting in and near the final ice-divide zone and of the history of the last glacial epoch. Relatively continental climates in all the studied areas except Sylarna, together with the nature of the country rocks, have tended to preserve the topographic forms exceptionally well.

The glacial land forms distinguished are divided into supraglacial, lateral, subglacial, and frontal and extramarginal (pp. 211, 228).

Here only the most important ones will be mentioned.

As the ice melted down in the mountains studied, ablation moraine increased on the ice surface (p. 212). On modern glaciers, ablation moraine accumulates in strange shapes and at times becomes arranged in ridges parallel to the ice edge (pp. 12–14, 223). Thus a glacier with a thick moraine cover may advance suddenly over broken terrain, developing large concentric fissures, in which ablation moraine slips down. Englacial moraine beds, melting out along glide planes, may also form parallel ridges. The debris which slumped into depressions and crevasses in Scandinavia was ultimately deposited on top of the subglacial deposits (p. 212). Ablation moraine is here present, particularly in broad mountain valleys and on intermontane plateaus.

Lateral drainage channels are numerous in the lower continental parts of the Scandes (pp. 212, 224, 226, 228; maps; Pls. XII–XIV). They are about equally abundant in all exposures, showing that insolation was not a decisive factor in the melting. When occurring in numbers, one below the other, they indicate the yearly thinning of the ice. When strictly lateral, they also record the ice slope. Lateral terraces of accumulation, especially when long, are still better indicators of the mean slope of the ice (pp. 73, 76, 90, 167, 213).

Subglacial chutes are common features (pp. 215, 225). They were formed either as downhill branches of lateral drainage channels or as independent gullies or ravines, which cross these channels (Pls. III, IV, XIII). They arise especially when streams with relatively warm water melt their way under the ice (p. 23). In the center of the valley several may join to form a master-channel (pp. 23, 190; Pl. IX). In Oviksfjällen (pp. 76, 225; Pls. I, III), Fjätervåla (pp. 121–24, 226; Pl. VIII), and Sylarna (pp. 192–96, 228; Pl. IX) there are abruptly turning ridges descending the hill slopes. No similar formations seem to have been described. The Swedish name "slukås," suggested by Dr. Mannerfelt, has been translated as "subglacially engorged esker" (pp. 47, 225), but perhaps "chute esker" would be better. The ridges are commonly 2–6 meters high and 10–20 meters wide at the base, but a few attain a height of 8 meters (pp. 76, 123, 193). They consist of current-bedded sand and gravel with a thin mantle of bouldery till. The chute eskers occur in re-entrants or coves and below irregular precipices. They may have been deposited in tunnels below the ice, the sand and gravel by streams, the till shell by the melting ice. On the valley floor, chute eskers from the valley sides may join to form an axial esker (pp. 82, 149, 176). In other cases, tunnel fillings produce a network of esker ridges (p. 83; Pl. IV).

Between the mountains there are large areas of so-called "dead-ice" moraine, which is characterized by a maze of hummocks, crooked uneven ridges, and numerous depressions and kettles, many of which contain lakes or ponds (pp. 88, 143–58, 181–83, 197–201, 216, 225–28). Some of the ridges consist of a core of glaciofluvial sand and gravel veneered by ablation moraine, while others are composed entirely of till. Many ridges may have been formed in tunnels under dead ice, receiving the till mantle at the final melting of the ice. Others have been formed at the ice margin, but none have been pushed together. Undisturbed subglacial accumulations indicate that the marginal ice was stagnant (p. 216).

In the lower mountains near the ice-divide zone there are, in the cols between the summits, dry ravines or canyons cut usually in solid rock (pp. 33, 41, 128, 217, 224–26; Pls. I, VI, X). These are called "col gullies" in the translation, but perhaps "col ravines" would be more appropriate. Most of the ravines are from a few to 20 meters deep; but Dromskåran is a striking box canyon, 40 meters deep and 900 meters long (p. 53; Pls. II, XI). These col ravines must have been cut by glacial streams when the summits melted out of the sloping ice. Since the water postulates strong ablation, the névé line must have stood decidedly higher than any col ravine.

The frontal and extramarginal deposits on the valley floors and plateaus were conditioned by the slope of the ground and the state of the ice lobe (p. 217). In level terrain and gentle counterslope the ice was relatively solid, and hummocky dead-ice moraine was formed under and at the ice margin (p. 181). In broken terrain and on forward-sloping ground the ice gradually broke up at the same time that it grew thinner and terminated in a tapering, ragged, drift-covered margin (pp. 118, 218). Severing of ice blocks can have taken place through comparatively fast melting of relatively drift-free parts of the ice, through water erosion, formation of fissures, or free-melting of ice blocks in depressions (p. 27). The detached ice blocks partly controlled drainage and deposition, the

latter taking place on, between, and just outside the blocks (pp. 80, 114). Push moraines have not been observed in the area. On its west side the ice dammed up numerous lakes in which it ended in a calving cliff (p. 118). The lakes well to the west of the ice divide are floored by varved glacial clay, but those near the ice divide are normally not. These latter seem to have lost their sediments by sudden drainages, which perhaps occurred when the rising water floated the ice edge and ran off underneath (Fig. 4).

The névé or snow line—the boundary between accumulation and dissipation on a glacier—is largely a function of the snowfall during the season of accumulation and of the temperature during that of ablation (p. 8). A large ice sheet has its snow line near the margin and is nourished mainly in an inframarginal belt, which essentially controls the marginal movements of the ice. As long as there is an area of snow accumulation, there is outflow of ice. A dead-ice belt at a distance from the ice center means only that, because of some obstacle, ice flow has ceased in that particular region. When the snow line has withdrawn to the top of the ice (glacier, ice cap, or ice-sheet remnant) and ablation exceeds nourishment on the entire ice, this is climatically dead (p. 9). A climatically dead ice is not necessarily stagnant, for in subaquatic situations sudden drainages, exceptional calvings, or topographically conditioned severings of ice blocks can release outflow (p. 32). The ice is dynamically dead only when it has lost all motion.

Since the snow line is the upper limit of excessive melting, above it the glacier normally runs up on the bordering rock wall, while below it there is melted a trench between the ice and the wall (p. 10). Since the summits of Oviksfjällen, Sonfjället, and other mountains studied in Härjedalen and Dalarna when emerging as nunataks were encircled by open water, as shown by col ravines, they must already have been below the névé line (pp. 10, 32, 34, 100, 224, 226). The last ice-divide zone lay 20–40 kilometers to the south and southeast of Oviksfjällen, whose highest summit attains 1,370 meters (pp. 28, 224; Pl. I). Assuming a mean slope of the ice surface of 1 meter in 100 meters, the ice divide had an elevation of some 1,600 meters when Oviksfjällen began to appear as nunataks (p. 32). Since the late glacial snow line cannot have been lower than 1,500 meters in Sylarna and rose inland, the ice divide may have been below the snow line when Oviksfjällen began to melt out. Thus the entire regional ice remnant, which may have been 40–50 miles wide, was then climatically dead and undergoing wastage.

The decrease in ablation from the ice edge upward is shown by the decreasing slope of the ice surface. In Oviksfjällen a lateral terrace and a lateral drainage channel indicate a slope of 3 in 100 for the first kilometer and of about 1 in 100 in the second or third kilometer (pp. 72–74). Mannerfelt assumes generally for these mountains an ice slope of 3 in 100 at the edge, 2 in 100 a few kilometers from the edge, and <1 in 100 for the inframarginal ice surface (p. 225). The annual downmelting, as recorded by the vertical distance between lateral channels, averaged 5 meters (p. 74). This marginal thinning means a yearly retreat of the ice edge on level ground of 150 meters.

After Oviksfjällen had become exposed, ice lobes lingered in the lowest valleys to the east (p. 67). Subglacial chutes and chute eskers testify to thin and decayed ice (pp. 22, 225; Pls. I, III). Fantastic landscapes of pits, kettles, lakes, knobs, and irregular, frequently anastomosing ridges show that the ice lobes were honeycombed by tunnels, rent by fissures, and split into blocks, under, between, and above which assorted drift and till were accumulated (Pl. IV). In lakes, ponded by the ice, the front retreated by calving.

Lateral drainage channels also illustrate the attenuation of the ice margin in other mountains. Thus in Sonfjället, situated some 10 miles southeast of the ice-divide zone, the slope of the marginal ice averaged 3.5 in 100 and the yearly thinning 4 meters (pp. 28, 102–9, 226). The annual retreat of the ice edge consequently measured 100–150 meters (p. 111). In Idrefjällen of northern Dalarna the ice slope averaged >2 in 100 (pp. 120, 125, 126, 226). In Transtrandsfjällen the marginal ice slope was about 3.5 in 100, the annual lowering 3 meters, and the yearly recession 90 meters (pp. 129, 142, 226).

In all the regions mentioned, the mean slope of the ice surface in the belt of ablation seems to have been about 1.5 in 100 (pp. 111, 142), which equals 79.2 feet per mile, or almost 2,000 feet in 25 miles. With this slope the ice edge would have been some 50 km. (30 miles) distant, when the highest lateral drainage channels were formed in Sonfjället (p. 111), i.e., the zone of melting may have been 50 km. wide. Clearly, the belt of ablation was not very wide, and any

zone of severed ice blocks was narrow at any one time.

The introductory stage of the Last Glacial in Europe was a severe local glaciation in the high mountains of Scandinavia, as suggested in the present area by large, well-developed cirques in Rendalssölen (pp. 157, 227), Rondane (pp. 160, 168–70), and Sylarna (pp. 173, 187, 209; Pl. IX). The large size of the cirques, puny moraines if any, and terraces in some cirques clearly show that these were excavated before the culmination of the latest glaciation, not, as previously held, during its final stage. They may have been eroded at the beginning of this glaciation as well as during earlier glacials. A similar dating has long been given the cirques in the mountains of New England.

The next main stage was the development of the ice sheet which ultimately covered all northern Europe. This sheet seems to have conserved, rather than destroyed, the topographic features of the high mountains in the central regions, such as cirques and sharp ridges (pp. 169–71, 210).

Finally came the stage of ice wastage, from the last part of which derive all the mentioned land forms except the cirques. This was the end of the Last Glacial in the lower mountains (pp. 135–36, 156). Not so, however, in Rendalssölen (pp. 157–59, 227), Rondane (pp. 160, 168), and Sylarna (pp. 173, 187, 203–9, 228), where glaciers were reborn in some of the old cirques. These glaciers were small and short-lived, but they cleaned out the cirques and locally sharpened the features. Peat bogs inside moraines show that the glaciation antedated the warm age of the Postglacial (pp. 168, 204). At present, Rondane touches the glaciation line and has some névé fields (p. 161), while Sylarna have a small glacier (pp. 173, 187, 208; Pl. IX).

It is a careful, level-headed, and important piece of research, appropriately dedicated to the outstanding student of modern glaciers, Professor Hans Ahlmann.

ERNST ANTEVS

Geology of Lau, Fiji. By HENRY S. LADD and J. EDWARD HOFFMEISTER. (Bull. 181.) Honolulu: Bernice P. Bishop Museum, 1945. Pp. 399; figs. 41, pls. 62.

The 180th meridian divides the Fiji Islands into a western group, including Vitilevu and Vanualevu, which are much larger than all the other islands combined, and an eastern north-and-south belt of about one hundred small islands, known as Lau. An excellent treatment of the geology of Vitilevu appeared in 1934 as Bishop Museum Bulletin No. 119 by H. S. Ladd and collaborators. That same year a University of Rochester expedition made a careful study of twenty-six of the Lau Islands to supplement earlier investigations, to tie the geological history of Tonga (visited by Hoffmeister in 1926) to that of western Fiji, and to obtain data bearing on the coral-reef problem. The present volume is their matured report.

The oldest rocks found in Lau are andesitic pyroclastics and flows, widely exposed, and probably not greatly older than the Lower (or Middle?) Miocene Futuna limestone resting on them. The Futuna is dominantly a bedded formation, rich in algae and Foraminifera but poor in corals. Its deposition was followed by emergence and widespread erosion. Volcanism (agglomerates and lava flows, chiefly of olivine basalt) again set in during the emergence in later Miocene times. The Ndalithoni (Pliocene) limestone on the flanks of certain islands indicates resubmergence of parts of Lau at least. Intermittant uplifts followed the close of the Tertiary, while, during intervening times of standstill, wave erosion and reef growth formed terraces around the margins of the islands. Lavas (Mango odinite) reached the surface of two of the islands after they were elevated.

The report takes up each island in turn, giving in detail its descriptive geology, the interpreted geologic history, and, for many of the islands, comparisons with earlier interpretations, some of which are particularly helpful in acquainting the reader with the major problems involved and how they have been attacked. Earlier researches in Lau were chiefly those of J. Stanley Gardiner, Alexander Agassiz, E. C. Andrews, W. M. Davis, and W. G. Foye.

Recognition of widespread, uplifted Tertiary deposits is prerequisite to the interpretation of the physiographic features. Some of the land forms in the limestone areas are explained in terms of organic growth, whereas others are evidently the results of chemical and mechanical erosion. Wave attack is of great importance along the coasts; but inland, mechanical erosion is unimportant and completely overshadowed by solution. Normal valleys do not form in the limestone areas of Lau; instead, solution makes basins of all sizes and shapes, which dominate the topography. Under favorable conditions solution may continue for appreciable distances

below sea-level, for a lenticular mass of fresh water underlies each island.

The prevailing basin shapes of the small limestone islands in Lau led early investigators to interpret them as elevated atolls. Ladd and Hoffmeister's detailed studies indicate that, for certain islands, this interpretation is probably correct; but, on the other hand, the limestones of many other islands having well-developed basins do not show elevated reef structure to support the atoll hypothesis. Their basin shapes cannot be attributed directly to organic growth; apparently these islands rose from the sea as unrimmed, limestone-veneered banks; solution then produced pits and caverns whose coalescence has gradually developed the basin form.

Davis, having accepted Gardiner's view that the basin-shaped islands of eastern Fiji represent elevated atolls and recognizing different types of reefs in five belts, trending north-northwest and south-southeast, postulated "a westward migrating anticline on which the islands ride up and down like bits of driftwood disturbed by a wave from a passing steamer." While the distribution of reef types which led Davis to this hypothesis is very suggestive, as viewed on the chart, Ladd and Hoffmeister have a different interpretation and do not agree with him that only Darwin's reef theories explain the reefs of this area. They believe that "Lau's reefs, both Recent and elevated, can be most satisfactorily explained without any form of Darwinian subsidence." In their opinion, the evidence of widespread elevation (rather than a migrating anticline) cannot be ignored. They could find no thick elevated reefs to fit the subsidence theory; in fact, their studies of the elevated limestones show that "true elevated reefs are rare in Lau and that most of them were formed between periods of uplift." The authors, however, have not attempted in this volume to discuss, except incidentally, the controversial subject of the origin of coral reefs. That will be treated in a separate paper on the antecedent-platform theory which they support.

The volume also includes the following reports: "Petrography of Igneous Rocks," by Harold L. Alling; "Petrography of Limestones," by Geoffrey W. Crickmay; "Chemical Composition of Limestones," by J. W. Sanders and G. W. Crickmay; "Larger Foraminifera," by W. Storrs Cole; "Echinoidea," by Hubert Lyman Clark; "Barnacles," by H. A. Pilsbry; and "Decapod Crustacea," by Mary J. Rathbun.

Calcareous red algae were the most abundant contributors to the Lau limestones; second in importance were the Foraminifera, followed by corals, mollusks, echinoids, and brachiopods. Most of the dolomite is secondary, for it is found replacing fossils, such as corals, which are known to contain originally nearly pure calcium carbonate. But in a few places the lack of extensive alteration of the material strongly suggests that the calcareous mud contained a high percentage of magnesium when deposited. Sanders and Crickmay believe that many of the dolomites received their magnesia by replacement soon after deposition of calcium carbonate and think it "reasonable to suppose that this addition is greatest where sediments are accumulating very slowly and least where sediments are quickly buried and thus to some extent removed from participation in whatever chemical reactions effect the replacement."

The *Geology of Lau* is valuable as a regional study of this portion of the Fijian Archipelago. But its importance extends well beyond the reaches of these islands, for some of the trustworthy factual information here presented bears pointedly on several controversial geologic questions which can only be settled by an abundance of sufficiently representative established facts.

R. T. C.

Pyrites Deposits of Missouri. By OLIVER R. GRAWE. (Missouri Geological Survey and Water Resources, Vol. XXX [2d ser.].) Rolla, Mo. 1945. Pp. 482; pls. 17; figs. 8.

This report is in two almost equal parts. The first half includes ten chapters dealing primarily with the geological aspects of the pyrites areas, while the second half consists of one chapter devoted to the history and description of 91 mines and prospects.

Six districts have sufficient pyrites to have encouraged prospecting, but only two have produced commercial pyrites. By far the most production has come from deposits in hematite-bearing sink structures of the north central Ozark plateau. The greater part of the book is devoted to these occurrences.

In the area of sink structures, Grawe describes the physiography, stratigraphy, and structure. He considers the relationship of the "sulphur ores" to the controlling geologic factors.

There are three chapters on the mineralogy of the sink-structure deposits. Mineral determinations are often supported by tables comparing spacing and intensity measurements from X-ray diffraction patterns. The pattern measurements of the mineral in question is compared to those of a known mineral. The general mineral paragenesis is apparent from field work, but verification and added details were obtained from studies of polished specimens. Many good microphotographs are reproduced. Spectrographic analyses were run on 55 samples of pyrite, affording a basis for comparing pyrites within and outside Missouri. Twenty-six samples of the oxidized ore (hematite) were spectrographically analyzed to determine the changes in minor constituents due to oxidation.

The last chapter on pyrites deposits of the sink structures treats the origin of the structures and their fills. Previous theories are outlined, and a list is presented of thirty facts which any theory of origin must recognize. In the author's theory, basin-shaped caves developed above the ground water. These were filled with ground water by a slight depression of the north central Ozark region. This water "was somewhat saline and charged with hydrogen sulphide similar to the present ground water in the sediments beneath the Pennsylvanian formations off the Ozark dome." It was the source of the sulphur. The iron was leached from weathering Pennsylvanian and other sediments by surface waters and taken into solution as ferrous bicarbonate. "The sink structure .... acted as a large leaching basin or funnel" and guided the surface ferrous bicarbonate charged waters downward into contact with the hydrogen sulphide bearing ground water.

".... Iron was precipitated as pyrites in accordance with the following reaction:

$$2Fe(HCO_3)_2 + 4H_2S + O_2 = FeS_2 + 6H_2O + 4\,CO_2 .$$"

When Missouri pyrites mining was at the height of its third productive period (1934–40), Grawe collected the vital statistics of 91 mines and prospects. This information, recorded and evaluated in the second half of Grawe's report, will form a starting-place for any future development of the pyrites-mining industries.

Although Grawe's theory of origin for the pyrites deposits of the north central Ozark plateau seems adequate, his treatment of the basin-like sink structures in which these pyrites occur needs further attention. Formed in Ordovician cherty dolomite, they are elliptical in plan and are usually rimmed by overlying sandstone, which lines the upper part of the basin and dips inward with increasing steepness toward the center. The sink structures are more extensive horizontally and vertically than the pyrite deposits, which range in size from very small to several hundred feet across. In one deposit, "sulphur ore" was mined 325 feet beneath the surface. The sink basins are lined with chert conglomerate, which extends up under the sandstone rim rock and down beneath the bottom of the deposit. At a number of mines, masses of an Ordovician dolomite, which once overlay the sandstone rim rock, have been observed within the sink structure, and, in one mine, Pennsylvanian sandstone and clay-shales were also present.

The occurrence of Pennsylvanian strata in the pyrites-bearing sink structures calls to the reviewer's attention an older (1943) Missouri Bureau of Geology and Mines report, by H. S. McQueen, on the *Fire Clay District of East Central Missouri*. The fire-clay deposits of which McQueen writes are largely sandstone-rimmed sink structures filled with Pennsylvanian sediments. The deposits are generally small in the northern part of the district and larger in the southern part, where they reach the proportions of the pyrites-bearing sink structures just to the south. McQueen writes that, in his opinion, "the occurrence of iron ore in a district just south of the southern district in structurally similar, sandstone-lined sink-hole type deposits, is a manifestation of the lower part of a sink-hole type structure of which the clay bearing portion is the upper part." The sink structures of the fire-clay district are filled with Pennsylvanian shales, clays, sandstone, and some coal. These fills have "subsided" to their present position. In some cases more than one period of subsidence can be recognized. In many instances the fills have been faulted, folded, and brecciated in this process of subsidence.

Several years ago the reviewer visited one of these clay-filled pits near Stanton, Missouri, on the south side of Route 66. The pit is one of the larger sink structures. A lasting impression was made by a 1-foot bed of coal standing essentially vertical and forming a coal lining for at least half the circumference of the pit.

Both McQueen and Grawe think of these sink structures in terms of open caverns later filled by pyrites and/or clay. Grawe, in speak-

ing of the pyrites-bearing structures, says: "The bowl-like shape of many deposits suggests that vadose water played the dominant role in the development of the structure." As the water table was approached, the development of the cavity would be slowed up and ultimately stopped. "The result would be a subterranean room characterized by a rubble-covered floor, by a chert wall and by a sagged ceiling of dolomite and sandstone. This room would be at or near the center of a sink structure marked by gentle dips at the periphery, but changing abruptly to nearly vertical dips at the cavern wall."

The reviewer has explored many caves in Missouri and elsewhere. If any one thing stands out about caves, it is their linear extent. Isolated bowl-shaped caves are unknown to the reviewer. Floors may collect great rubble piles, but cherty dolomites do not produce chert concentrates on cave walls. Where sandstone roofs have been observed, they stand boldly in their stratigraphic position, until they partially or wholly collapse to add to the rubble floor.

McQueen, as well as Grawe, believes the sink structures developed above the ground-water table. However, Grawe records one sink structure which extends more than 325 feet below the ridge slope on which it is located, and many structures are recorded as occurring in present valley bottoms.

Since the present Ozark plateau has never been more deeply dissected than today, sink structures which extend below the present water table must have developed under phreatic conditions.

Grawe, in the study of the pyrites-bearing sink structures, uses the word "collapse" in many references to the anomalous stratigraphic position of some rock in the sink structures. McQueen, speaking of the clay-filled structures, also uses the word "collapse," but in some cases he modifies "collapse" by adding "or subsidence," and in many cases he refers only to "subsidence." Thus McQueen recognizes in the clay-filled sink structures a movement slower than that which might be supposed to follow collapse into open cavities.

In 1940, J H. Bretz published a paper in the *Journal of Geology* on "Solution Cavities in the Joliet Limestone of Northeastern Illinois." No reference is made to this paper by either Grawe or McQueen. The features which Bretz describes are elliptical, joint-controlled basins, ranging from a few feet to 150 feet in length and up to more than 40 feet in depth. The features diminish with depth and extend from the surface downward. The walls are a series of bedding-plane controlled moldings, which may overhang as much as 5 feet. All basins are filled with Pennsylvanian clays, with some sandstone and coal. In some basins the clay fill contains large blocks of Silurian limestone with a lithology that is not exposed in any of the basin walls, thus presumably coming from higher strata. The moldings of the basins in contact with the clay fill are slickensided on both upper- and undersides by motion of the fill down into the basin. Some small chert fragments from the clay fill mark the moldings with a long solution gouge, which leads to a small pit which still contains a chert fragment, imbedded in the limestone by the downward drag of the clay fill. The clay fill has been squeezed, faulted, brecciated, and sheared as it has pinched and swelled down into the irregularities of the basins. Sandstone lenses have been complexly folded and sheared, but not broken. A coal seam 1 foot thick, present as a horizontal bed on the flank of one of the basins, was traced down vertically as a thin pinching, swelling, and even overturned coal seam, 27½ feet into the basin and then up on the opposite side to join its horizontal counterpart on the other flank of the basin. These and many other features indicated to Bretz that the invasion of the clay fill was very slow and that solution was going on at the clay-limestone contact while the fill was subsiding and was the cause of the subsidence.

Bretz concludes: "No pre-Pennsylvanian karst topography survives in these cavities. . . . . If there were sinks and caves at the time, they have since been modified by further solution under weight of overlying Pennsylvanian sediments which constantly subsided into the enlarging joint crevices."

The similarities of these solution cavities, except for size, to the sink structures of the Ozark plateau are striking. It may be possible that a better answer to the origin of the Missouri Ozark plateau sink structures can be found in a study of solution cavities in northeastern Illinois.

Aside from these considerations, Grawe's report is a comprehensive study on deposits which have had little previous attention. Both practical and academic, it is a valuable contribution to knowledge of Missouri geology.

PAUL HERBERT

Fortress Islands of the Pacific. By WILLIAM HERBERT HOBBS. Ann Arbor, Mich.: Edwards Brothers, Inc., 1945. Pp. 186; figs. 107. $2.50.

Professor Hobbs has long been a student of the Pacific islands and in 1921 made extended cruises in Japanese and American warships within the Japanese-mandated area, where he had exceptional opportunities to study and photograph many of the islands that have since been fortified. Recognizing the world-wide interest in the western Pacific awakened by the decisive campaigns conducted there and realizing the vital importance of many of these islands in plans for the future stability of our civilization, Professor Hobbs has brought together in very readable form the results of his own studies, supplemented by the principal pertinent facts obtainable from the scattered literature.

The author builds his book on geologic foundations, recognizing that the various modes of origin of the islands have determined in large part their special features and their military importance. They are divided, first, into "strewn islands" (primarily basaltic volcanoes, with or without capping organic reefs) and "arcuate islands," aligned along festoon-like mountain folds around the western borders of the Pacific. The reader gets the impression that the volcanoes of the strewn islands developed largely on land prior to a great sinking of the Pacific basin and submergence by that ocean. The alternative that they have been built up from the floor of the ocean by submarine lava outpourings is not mentioned. Sinking, however, harmonizes well enough with the Darwinian hypothesis for the origin of barrier reefs and atolls, the only coral-reef hypothesis here considered. This great subsidence of the Pacific basin is also held responsible for flexing the rising mountain arcs on the western margin of the basin. The surficial movement is pictured as being from the outer or convex side of the arcs, producing in front a trough or foredeep, next an upfold, which becomes inclined due to underthrusting if the process proceeds far enough, while volcanoes with characteristically andesitic lavas appear on the concave side of the arcs.

A chapter is devoted to each of the following types of "strewn islands": "Group Volcanoes (Hawaiian, Samoan islands, etc.)"; "Volcanoes (Eastern Carolines, Panape, etc.)"; "Almost-Atolls (Truk, Gambier, etc.)"; "Atolls (Kwajalein, Tarawa, Funafuti)"; "Part-raised Atolls (Wake, Christmas Island)"; and "Raised Atolls (Baker, Nauru)"; while two chapters each are given to "Newborn Arcuate Islands (Aleutians, Okinawa, Marianas, etc.)" and "Youthful Arcuate Islands (Yap, Bismarck, and Solomon archipelagoes, Fiji, etc.)." These constitute the major part of the book. They are concise, replete with interesting historical accounts and general information, and abundantly illustrated with maps and pen-and-ink drawings by the artist, W. B. Shaw, from the author's photographs. Brief discussions of "Catastrophic Visitations" (earthquakes, earthquake sea-waves, and hurricanes) and "Network of Essential Pacific Bases," with a classified Bibliography for further reading, complete the volume.

For anyone wishing a little essential information on the various islands of the Pacific, this will be a very useful reference book. The many maps of individual islands, atolls, or groups of islands are a commendable feature.

R. T. C.

Stratigraphy of the Marmaton Group, Pennsylvanian, in Kansas. By J. M. JEWETT. (State Geological Survey of Kansas, Bull. 58.) Lawrence, 1945. Pp. 148; pls. 4.

Rocks of the Marmaton group of Middle Pennsylvanian age outcrop diagonally across the southeast corner of Kansas in a belt about 100 miles long and 10–25 miles wide. They consist of various types of shale, limestone, and sandstone with a few thin coals, and they attain a thickness of about 250 feet. The group is divided into eight formations, which, in turn, are subdivided into nineteen named members.

This report is based on field work which began in 1928 and involved the tracing of numerous thin units across the state of Kansas and into neighboring parts of Missouri and Oklahoma. The attention given to details is evidenced by the 203 stratigraphic sections, measured to tenths of a foot or less, which constitute the last half of the bulletin. Such work in several states carried on during the last twenty years has entirely demolished the myth that the Pennsylvanian system is a hodgepodge of lenticular beds, few of which can be traced for any distance or correlated with any certainty. The continuity of some conspicuous Upper Pennsylvanian limestones in Kansas has long been known; but it is now evident that many thinner beds, some measurable only in inches,

are equally regular in their development throughout very wide areas.

The main part of the report is devoted to detailed descriptions of the various formations and members and is accompanied by four plates of correlated columnar sections, showing the developments of the four limestone formations and associated beds. It is a good example of the presentation of thorough and painstaking field work. Important though this may be to local geologists or specialists in Pennsylvanian stratigraphy, the concluding chapter entitled "Cyclical Deposits" is certain to be of much greater general interest.

After a review of present concepts regarding cyclic deposition, including a brief differentiation of cyclothems and megacyclothems and mention of the several theories that attempt to explain their formation, the cyclic repetition of strata within the Marmaton group is described. Four megacyclothems are recognized which consist of fifteen well-developed and several other poorly developed cyclothems. Different types of strata are contrasted, and explanations of their significance in the cyclical sequences are offered. Finally, the principal characters of the four megacyclothems and their subordinate cyclothems are presented.

J. MARVIN WELLER

Geology and Mineral Resources of the Jackson Purchase Region, Kentucky. By JOSEPH K. ROBERTS and BENJAMIN GILDERSLEEVE. Paleozoic geology by LOUISE BARTON FREEMAN. (Commonwealth of Kentucky, Department of Mines and Minerals, Geological Division, Ser. VIII, Bull. 8.) Frankfort, 1945. Pp. vii+126; figs. 21, with geologic map and correlation chart of the Tertiary, Kentucky–Alabama.

The Jackson Purchase region, acquired by the state from the Chickasaw Indians in 1818, includes eight counties at the western tip of the state, bounded on three sides by the waters of the Tennessee, the Ohio, and the Mississippi rivers. The publication dealing with the geology of this region is divided into five sections: an Introduction which gives the general geographic setting, a section on Paleozoic structure and stratigraphy, a third division devoted to Cretaceous stratigraphy, followed by a section on Tertiary stratigraphy, and a final section discussing the mineral resources of the area.

The only exposures of pre-Cretaceous rocks to be found in the region are confined to a narrow belt of Mississippian rocks adjacent to the Tennessee River at the extreme eastern edge of the map area. Virtually all the information on the stratigraphy and structure of the Paleozoic beds has been obtained from cuttings taken from oil test wells. Descriptions are given of Paleozoic formations from Middle Ordovician through Mississippian. Two structural maps have been compiled, one with contours drawn on the base of the Upper Cretaceous and the second on the top of the Everton (Chazyan). The structural picture is relatively simple, but considerable movement is indicated between Ordovician and Upper Cretaceous by the discordance of structures on the two maps. It should be pointed out that since the data for structural control are very limited because of the small number of wells in the area, the structure is likely to be far more complex than is indicated. Nevertheless, the information is sufficient to shed considerable light on the stratigraphy and structure of a region about which little has been known heretofore. It is the reviewer's opinion that Mrs. Freeman, who was responsible for this portion of the report, has made a significant contribution.

Most of the field work for the sections of the report dealing with Cretaceous and Tertiary stratigraphy was done by Roberts during the summer of 1929. Much of this material has been published in earlier reports. The author recognizes three formations in the Upper Cretaceous within the region, namely, the Tuscaloosa, the Eutaw, and the Ripley. He has divided the Tertiary and later into the Porters Creek (Midway) formation, the Holly Springs and Grenada formations (Wilcox), the Jackson formation, Plio-Pleistocene sand and gravel, and Pleistocene loessal deposits. Each formation, together with its structural features, is described in detail.

The section covering mineral resources was prepared by Gildersleeve and is devoted almost entirely (26 out of 32 pages) to the clay resources within the Cretaceous and Tertiary sediments. The various clay horizons are discussed, and detailed sections are given at localities where clays have been developed commercially. Tests on certain clays have been included, as well as flow sheets of operations where they are mined. Other resources of the area are discussed briefly.

The geologic map which accompanies the

bulletin has a scale of 2 miles to the inch and is reproduced in color, making a valuable addition to the report.

VINCENT E. NELSON

Geology and Mineral Resources of the Burkes Garden Quadrangle, Virginia. By BYRON N. COOPER. (Virginia Geological Survey Bull. 60.) Virginia: University, 1944. Pp. 299, figs. 11, tables 5, pls. 21, including geologic map and structure sections.

Burkes Garden is a topographic basin located in the Appalachians of western Virginia. Excavated on relatively nonresistant Ordovician limestones and clastics, it is almost completely encircled by erosional scarps, approximately 1,000 feet high and capped by Clinch sandstone. Structurally, the feature is an elliptical dome, 8 miles long and 4 miles wide, with its axis of elongation parallel to the general trend of Appalachian folding. Unique among the topographic-structural forms of the fold belt, Burkes Garden has given its name to a quadrangle which, except for 2 or 3 square miles in its northwestern corner, lies wholly within the faulted and folded Paleozoics comprising the so-called "Valley and Ridge Province."

Bulletin 60 of the Virginia Geological Survey, by Byron N. Cooper, offers a descriptive treatment of this quadrangle which will long serve as a standard of reference for workers in southern West Virginia, western Virginia, and eastern Tennessee.

Two-thirds of the 300-page text are devoted to stratigraphy. A foot-by-foot account of 17,000 feet of sediments ranging from the Rome formation (upper Lower Cambrian) to the Lee formation (Lower Pottsville) does not normally make exciting reading. Yet, by good writing, intimate knowledge of stratigraphy, not only of this quadrangle but of the central Appalachians, and a familiarity (which must have been acquired by long and critical study) with the work performed by other geologists in this region, Cooper manages to do the impossible, namely, to hold the reader's attention.

The stratigraphic section contains several features which are inherently interesting. Despite the high ratio of calcareous rocks, the area occupied an inshore situation throughout Paleozoic time, and the recurrent shifts of the strand line created a few surprising breaks in the section and a number of baffling changes in lithology and thickness within the limits of the quadrangle. Cooper does not fully appreciate the structural and geographic compression which the section has undergone, and it would be phenomenal if all his judgments on correlation are right. But he does demonstrate the need for caution in accepting the generalized correlations and nomenclature of some well known geologists who have sponsored most of the publications dealing with this and contiguous areas.

The reviewer is not qualified to judge all of the issues which Cooper has raised, but he must offer a criticism of the author's treatment of the Cliffield formation-group. In the central and northern parts of the quadrangle the Cliffield (lower Middle Ordovician) is 500 feet thick, and it thickens to approximately 800 feet southeastward. Where thin, it is divisible into five fairly persistent and differentiable units, which Cooper treats as "members" of the Cliffield "formation." Where thick, it is divisible into seven units, which Cooper dignifies as "formations" within the Cliffield "group." Four of the seven units are correlated from one section to the other, with minor changes in lithology and moderate variations in thickness. The reviewer can find no justification for altering the status of the Cliffield from a formation to a group, or of the members to formations. Although doing so may emphasize the marked stratigraphic change which occurs, the alteration injects unnecessary confusion into the nomenclature.

Aside from this single lapse, the complex problems and the endless details are masterfully handled. It is to be hoped that subsequent bulletins may provide comparable expository data which will make it possible to explain the changes and to verify the correlations from Tennessee to West Virginia and Pennsylvania.

Only 14 pages of the bulletin are devoted to structure, and the job is not too satisfactorily done. But the geologic map and the structure sections which comprise Plate I will provide material for hours of study. It is probable that the reader will prefer to reconstruct the ensemble of folds and minor faults in the individual thrust sheets which comprise the major structural elements of the Burkes Garden quadrangle, with no more than casual reference to the piecemeal descriptions of individual structures which Cooper contributes. He will certainly restore the structure of the Burkes Garden dome on some higher stratigraphic horizon than the Clinch in an effort to appreci-

ate the true stature of this interesting structure. He will also make some attempt to interpret the genetic relationships between the Burkes Garden dome and the curvature and tear faults along the Saltville-Bland fault to the south and the discontinuity in the fault to the north near the Narrows overthrust. Possibly Cooper was wise in restricting the text to exposition and in avoiding structural interpretations, which would inevitably become the subject of controversy. The geologic map and five structure sections constitute a major contribution to Appalachian orogenic phenomena, and it may be unfair to ask more of the author.

Cooper threads his way deftly through the maze of contradictions commonly known as "Appalachian geomorphology," making a few contributions that will stand amid the falling ruins of theory and speculation. Chief of the author's contributions is a brief analysis of the elevations of ridge crests in relation to the thickness and local structure of ridge-making formations. He comes out with the only possible conclusion, namely, that the elevations of essentially horizontal crests are a function of resistance, thickness, and dip, and not an index of cyclic erosion. Unfortunately, he goes somewhat beyond the conclusion warranted by his facts when he implies that denudation of horizontal surfaces on weak formations may likewise be noncyclic. Such an implication, however, can be supported by citation of good, if not reliable, authorities; and Cooper cannot be held for the solution of geomorphic problems on which all the doctors seem to disagree.

Following a brief but adequate treatment of the water resources and of the limited suite of rock and mineral products available in the quadrangle, Cooper concludes his volume with a résumé of the geologic history. As a summary of Paleozoic sedimentation, this section is good; but it follows the work of older geologists too uncritically in certain particulars. For example, this sentence (p. 280), "Toward the close of pre-Cambrian time, this region was worn down to an essentially base-leveled surface," will undoubtedly be read with general approval. On the same page, however, Cooper mentions that the Rome formation, the oldest exposed in the quadrangle, is underlain eastward by 1,000–1,800 feet of the Shady formation, "which in turn overlies several thousand feet of coarse sandstone and conglomerate of Chilhowee group."

These kinds of sediments do not accumulate to thicknesses of several thousands of feet on a base-leveled surface. Someday American geologists may attempt to reconcile the coarse clastic character of the Lower Cambrian series in the southern Appalachians; the thousand feet (and over) of relief at the base of the Cambrian in Wisconsin, Michigan, and Minnesota; and the hundreds of feet of relief on the pre-Cambrian floor in the Saint Francis Mountains of Missouri, the Black Hills of South Dakota, and the Adirondacks of New York, with the widely held concept of a late pre-Cambrian peneplain.

It is not fair to hold Cooper responsible for the mental lapses of his predecessors and contemporaries. He has done an excellent piece of areal and stratigraphic work, which it has been a pleasure to read and a privilege to review. It is commended to those who wish to understand the south-central Appalachians, as well as to those who wish to examine a model of one type of state-survey bulletin.

HOWARD A. MEYERHOFF

A Survey of Weathering Processes and Products. By PARRY REICHE. ("Publications in Geology," No. 1.) Albuquerque: University of New Mexico Press, 1945. Pp. 87; figs. 6. $0.75.

This book admirably describes and summarizes the various ways by which rocks are altered in weathering, "the response of materials which were in equilibrium within the lithosphere to conditions at or near its contact with the atmosphere, the hydrosphere, and .... the biosphere," and discusses the end-products of weathering, which are the source materials for sedimentary beds. Written by a geologist for geologists, it organizes present knowledge, chiefly from the sixty-seven papers included in the Bibliography, into a complete and clear outline of the subject, unobscured by too much descriptive detail. The author has not kept to the time-honored separation between soil-forming processes, due directly or indirectly to life, and inorganic weathering processes, since he believes the two are inseparably associated. The chapter on soil-forming processes should be of special value to the geologist, since in late years this study has been more and more divorced from our science, yet has many important geological aspects.

The book consists of five chapters, "Physical

Processes," "Chemical Processes and Reagents," "Results of Chemical Weathering," "Soil-forming Processes and Soils," and "Factors of Relief and Time."

The author concludes that purely physical processes of weathering are of secondary importance, only unloading and crystal growth being significant. Under chemical weathering, whose importance he considers "hard to overestimate," he discusses the fundamental laws and, in some detail, the roles in the weathering process of colloidal chemistry, hydration and hydrolysis, oxidation, reduction, and exchange reactions. The end-products of weathering are described, as well as the course of chemical weathering, with a discussion of studies on the relative mobilities of the chemical constituents of rocks and the relative stability and persistence of minerals. The discussion of soils is quite incomplete but probably adequate as an introduction to the subject. A brief discussion of peneplain soils is presented, and the laterite problem is succintly reviewed.

The book is a reference work which should be in every geologist's library; it can also serve as an introduction to the study of weathering and as a springboard to further study of the subject.

LOU WILLIAMS

The Snellius Expedition in the Eastern Part of the Netherlands East Indies (1929–1930) under Leadership of P. M. Van Riel, Vol. V: *Geological Results;* Part 3: "Bottom Samples"; Sec. I: "Collecting of the Samples and Some General Aspects." By PH. H. KUENEN. Pp. 46; figs. 6; pls. 2; tables 14. Sec. II: "The Composition and Distribution of the Samples." By IR. G. A. NEEB. Pp. 213; figs. 27; pls. 11; tables 32; maps 3. Leyden: E. J. Brill, 1942, 1943.

This report, which describes 382 samples collected by the Snellius Expedition, is divided into two sections.

Section I, by Kuenen, four chapters long, deals with the collection, treatment, and general interpretation of the sediments sampled. An improved Ekman sampler was used to secure most of the samples. Thinner walls and a more effective water-exit valve made possible the collection of longer cores. The organic content of the sediments averaged 1 per cent and varied directly with the clay content and depth of deposition and inversely with the lime content. Chemical analyses showed an abnormally high percentage of Na_2O. The radium content, however, is normal for deep-sea deposits, in spite of the unusually rapid sedimentation in the East Indian basins. The radioactivity is, therefore, a property of the sedimentary particles themselves; for, if the radioactivity were due to independent precipitation, it would be diluted and be lower than normal.

Kuenen discusses the anaerobic sedimentation in Kaoe Bay of Halmaheira Island and also the general absence of stratification and annual rhythms in the sediments of the whole area surveyed. The rate of postglacial sedimentation in the basins is estimated at 50 cm. per thousand years. Slumping and sliding of the sediments on the basin floors was found to be uncommon.

Section II, by Miss Neeb, contains eight chapters and comprises four-fifths of the report. The sediments sampled were classified into six major groups; globigerina ooze, red clay, coral mud and sand, terrigenous mud, volcanic mud, and volcanic plus terrigenous muds. Samples from earlier expeditions in the area, namely, the Cachelot, Challenger, Gazelle, and Siboga, were reinterpreted to conform to the above classification. A lengthy description of the mechanical and mineralogical composition of the individual samples is accompanied by many tables of grain-count results. Certain mineral suites of volcanic muds were found to be diagnostic of individual volcanos. On the basis of both light- and heavy-mineral studies, the terrigenous muds were subdivided into five groups, depending on whether the detrital constituents were derived from crystalline schists, acid igneous rocks, intermediate to basic metamorphic rocks, quartziferous sediments, or old volcanic rocks.

The results of Miss Neeb's detailed microscopic work and that of earlier surveys is embodied in a 1:4,000,000, six-color chart (about 24×24 inches), showing areal extent of the sediment types. Maps depicting the distribution of Tambora volcanic ash and the relative lime content of the sediments also accompany this report.

From volcanic-ash horizons of known age, the rate of accumulation of terrigenous muds was calculated to be 65 cm. per one thousand years, a rate fifty times that found by Schott for the Atlantic. The rate for globigerina ooze of 1 cm. per one thousand years agrees with Schott's determination.

The X-ray analyses of the mud fractions of several samples revealed a decrease in contents of quartz, muscovite, and feldspar and an increase of montmorillonite with a decrease in grain size.

Calcareous and siliceous organisms of the sediments are briefly treated. Miss Neeb can see no reflection of Pleistocene climate in the faunas of the sediments sampled.

The last chapter is devoted to the secondary minerals encountered. The pyrite content was found to be unrelated to depth of deposition and directly proportional to the carbon content.

An extensive Bibliography, together with a list of earlier publications concerning the Snellius Expedition, accompanies this report.

ROBERT NANZ

The Charnockite Rocks of Mysore (Southern India). By B. RAMA RAO. (Mysore Geological Department, Bull. 18.) Bangalore, 1945. Pp. iv+199; pls. 14. 3 Rs.

"Charnockite," a term originally used by Sir Thomas Holland to designate a variety of hypersthene granite, was later applied by him, in the expression "charnockite series," to a series of Indian rocks associated with the original charnockites and showing every gradation from granite through intermediate and basic types to ultrabasic types, all characterized by the presence of hypersthene. Similar rocks have since been described from widely separated regions of the earth, and there has been much controversy as to whether they represent a series of igneous differentiates, as Sir Thomas supposed, or whether some varieties represent metamorphosed (soaked) sedimentary material.

Rao now gives the results of a prolonged study of such rocks occurring in Mysore and constituting a northerly extension of the type areas. He concludes that the complex embraces a series of ancient sediments with intercalated sills and sheets of intrusive basic igneous rocks, showing notable differentiation and reaction effects with the sediments. Into this complex was intruded granitic magma, which greatly modified the older rocks, largely by soaking, and was itself modified by contamination with basic material, with consequent production of the intermediate and acid types of the charnockites.

N. L. B.

Bibliography on the Petroleum Industry. By E. DEGOLYER and HAROLD VANCE. (Bulletin of the Agricultural and Mechanical College of Texas, Fourth ser., Vol. XV, No. 11.) College Station, Tex., 1944. Pp. xxxii+730. $3.00.

The *Bibliography* was assembled from DeGolyer's personal files, the bibliography of the Petroleum Engineering Department at the Agricultural and Mechanical College of Texas, and a complete bibliography on the air-gas lift furnished by S. F. Shaw.

The references are listed in chronological order under approximately nine hundred headings, arranged according to a decimal system of classification. The major subject groupings are: (1) "General Data on Petroleum and Related Industries"; (2) "Geographical Distribution of Petroleum, Oil Fields, Properties, and Districts: Descriptions and Maps"; (3) "Physical and Chemical Properties of Petroleum, Examination, Testing, and Sampling"; (4) "Exploration and Prospecting for Petroleum and Other Bitumens: Geology of Petroleum"; (5) "Development of Deposits of Oil, Gas, and Other Bitumens"; (6) "Production of Petroleum and Natural Gas and Related Hydrocarbons"; (7) "Transportation, Storage and Gauging of Petroleum and Natural Gas"; (8) "Oil Refineries, and Refinery Practice"; (9) "Utilization of Petroleum and Its Products"; (10) "Economics of the Petroleum Industry."

The book contains a decimal index as well as an alphabetical subject index.

CHESTER JOHNSON

PUBLICATIONS RECEIVED

Administration Report of the Government Mineralogist for 1944. By L. J. D. Fernando. Colombo, Ceylon: Department of Mineralogy, June, 1945.

Alguns aspectos da geologica dos granitos do norte de Portugal. By Carlos Teixeira. Publicações da Soc. Geol. de Portugal. Porto: Imprensa Moderna, 1945.

Amenability of Various Types of Clay Minerals to Alumina Extraction by the Lime Sinter and Lime-Soda Sinter Process. By R. E. Grim, J. S. Machin, and W. F. Bradley. Illinois State Geological Survey Bulletin 69. Urbana, 1945.

Annual Report of the Director of the Department of Terrestrial Magnetism. Carnegie Institution of Washington. Reprinted from Year Book Nos. 41, 42, 43, for the years 1941–42, 1942–43, 1943–44. Washington, 1945.

Artesian Water in Southeastern Georgia. By M. A. Warren. Georgia State Division of Conservation. Atlanta, 1945.

Beiträge zur Kenntnis des Chemismus der finnischen Minerale. By Lauri Lokka. Commission géologique de Finlande Bulletin 129. Helsinki, 1943.

Bibliography of the Geology and Mineral Resources of Utah. By Bronson F. Stringham. Bulletin of the University of Utah, Vol. XXXIV, No. 15. Salt Lake City, April, 1944.

The Bonding Action of Clays. Part II. Clays in Dry Molding Sands. By Ralph E. Grim and F. Leicester Cuthbert. Illinois State Geological Survey, Report of Investigations No. 110. Urbana, 1946.

The Cheyenne Sandstone and Adjacent Formations of a Part of Russell County, Kansas. By Ada Swineford and Harold L. Williams. University of Kansas Publications Bulletin 60; 1945 Reports of Studies, Part 4. Lawrence, December, 1945.

Diagnostic Criteria for Clay Minerals. By W. F. Bradley. Illinois State Geological Survey, Report of Investigations No. 115. Urbana, 1946.

Earth Beneath: An Introduction to Geology for Readers in New Zealand. By C. A. Cotton. Wellington: Whitcombe & Tombs, Ltd., 1945.

The Easterday Abandoned Channel of the Ohio River. By Willard Rouse Jillson. Frankfort, Ky.: Roberts Printing Co., 1946.

The Expanding Mineral Industry of the Adirondacks. By Herman F. Otte. State of New York, Department of Commerce, Publication No. 10. February, 1943. Reprinted August, 1944.

Exploration for Oil and Gas in Western Kansas during 1944. By Walter A. Ver Wiebe. University of Kansas Publications, State Geological Survey of Kansas Bulletin 56. Lawrence, 1945.

Ferruginous Bauxite Deposits in Northwestern Oregon. By F. W. Libbey, W. D. Lowry, and R. S. Mason. Oregon Department of Geology and Mineral Industries Bulletin 29. Portland, 1945.

General Features of Colorado Fluorspar Deposits. By Doak Cox. Colorado Scientific Society Proceedings, Vol. XIV, No. 6. Denver, 1945.

Geology and Groundwater Resources of the Coastal Area in Mississippi. By Glen Francis Brown *et al.* Mississippi State Geological Survey. University, Miss., 1944.

Geology and Ground-Water Resources of Thomas County, Kansas. By John C. Frye. University of Kansas Publications, State Geological Survey of Kansas Bulletin 59. Lawrence, 1945.

Geology of Red Deer and Rosebud Sheets, Alberta. By John A. Allan and J. O. G. Sanderson. Report No. 3. Edmonton, 1945.

Geology, Ore Deposits, and Mines of the Mineral Point, Poughkeepsie, and Upper Uncompahgre Districts, Ouray, San Juan, Hinsdale Counties, Colorado. By V. C. Kelley. Colorado Scientific Society Proceedings, Vol. XIV, No. 7. Denver, 1946.

Granodioritic Intrusions and Their Metamorphic Aureoles in the Young-Tertiary of Central Flores. By H. A. Brouwer. Reprinted from: Geological Expedition to the Lesser Sunda Islands under the Leadership of H. A. Brouwer, Vol. IV, pp. 291–317. Amsterdam: N. V. Noord-Hollandsche Uitgevers Mij., 1942.

Illinois Mineral Industry in 1944. By Walter H. Voskuil and Douglas F. Stevens. Illinois

State Geological Survey, Report of Investigations No. 109. Urbana, 1945.

Ilmenite, Monazite, and Zircon; Gems and Semi-precious Stones of Ceylon. By D. N. Wadia and L. J. D. Fernando. Records of the Department of Mineralogy of Ceylon, Professional Paper No. 2. Colombo: Ceylon Government Press, 1945.

Industrial Limestones and Dolomites in Virginia: New River–Roanoke River District. By Byron N. Cooper. Virginia Geological Survey Bulletin 62. University of Virginia, University, Va., 1944.

The Keene Dome, Northeast McKenzie County, North Dakota. By Charles Nevin. The Subsurface Stratigraphy of the Nesson Anticline. By Wilson M. Laird. North Dakota Geological Survey Bulletin 21. Grand Forks, 1946.

Kinkaid Corals from Illinois and Amplexoid Corals from the Chester of Illinois and Arkansas. By William H. Easton. Illinois State Geological Survey, Report of Investigations No. 113. Urbana, 1945.

Light-Weight Aggregate. By William Clifford Morse, Thomas E. McCutcheon, and Bernard F. Mandlebaum. Mississippi State Geological Survey Bulletin 61. University, Miss., 1945.

List of Publications for the Year 1943. List of Publications for the Year 1944. Carnegie Institution of Washington, Department of Terrestrial Magnetism. Washington, D.C., 1943, 1944.

Los Vertebrados del Terciario continental colombiano. By Jose Royo y Gomez. Separado de la Revista de la Academia Colombiana de Ciencias Exactas, Fisico-Quimicas y Naturales, Vol. VI, No. 24. 1945.

Manganese and Quartzite Deposits in the Lick Mountain District, Wythe County, Virginia. By F. W. Stead and G. W. Stoss. Geological Survey of the Department of Interior, University of Virginia. University, Va., 1943.

Marine Pool, Madison County: A New Type of Oil Reservoir in Illinois. By H. A. Lowenstam and E. P. DuBois. Illinois State Geological Survey, Report of Investigations No. 114. Urbana, 1946.

Matemec Lake Map—Area Saguenay County. By E. W. Greig. Province of Quebec, Canada, Department of Mines, Division of Geological Surveys, 1945.

Mica. By R. S. Matheson. Department of Mines, Mineral Resources of Western Australia Bulletin 2. 1944.

Mineral Industries Research. Pennsylvania State College Bulletin, School of Mineral Industries; Pennsylvania State College, State College, Pennsylvania, Circular 20. Obtainable free of charge upon writing.

Mineralogical and Physical Composition of the Sands of the Oregon Coast from Coos Bay to the Mouth of the Columbia River. By W. H. Twenhofel. State of Oregon, Department of Geological and Mineral Industries Bulletin 30. Portland, 1946.

The Mining Industry of the Province of Quebec in 1943. Canada Department of Mines. Quebec: Redempti Paradis, Printer to H. M. the King, 1944.

Mining Properties and Development in Abitibi and Temiscamingue Counties during 1944. Parts I, II, and III. By W. N. Ingham. Province of Quebec, Canada, Division of Mineral Deposits. Quebec, 1945.

Mining Review for the Half-year Ended 31st. December, 1944. No. 81. Department of Mines, South Australia. Issued under the Authority of the Hon. A. Lyell McEwin, Minister of Mines. Adelaide, 1945.

Moisie Area, Saguenay County. By Carl Faessler. Department of Mines, Division of Geological Surveys. Quebec: Redempti Paradis, Printer to H. M. the King, 1945.

Moränenuntersuchungen im westlichen Nordfinnland. By V. Okko. Suomen Geol. Toimikunta, Bulletin de la commission géologique de Finlande, No. 131. Helsinki, June, 1944.

Natural Light-Weight Building Block Materials of New Mexico. By T. D. Venjovsky and D. M. Clippinger. New Mexico School of Mines, State Bureau of Mines and Mineral Resources. Socorro, N.M., October, 1945.

North Dakota Weather and the Rural Economy. By J. M. Gillette. State Historical Society of North Dakota, North Dakota History, Vol. XII, Nos. 1–2, January–April, 1945. Bismarck, 1945.

Notes on Building-Block Materials of Eastern Oregon. By Norman S. Wagner. State of Oregon, Department of Geology and Mineral Industries, G.M.I. Short Paper No. 14. Portland, 1946. Price $0.10.

Notes on Pleistocene and Recent Tapirs. By George Gaylord Simpson. Bulletin American Museum of Natural History, Vol. LXXXVI, Art. 2. New York, 1945.

Oil and Gas in Eastern Kansas. By John Mark Jewett and George E. Abernathy. University of Kansas Publications, State Geological Survey of Kansas Bulletin 57. Lawrence, 1945.

Oil and Gas Investigations. By Ralph G. Lusk and W. F. Bailey. Map, Stratigraphic Column, Well Data, and Explanations. Department of Conservation, Division of Geology, Tennessee. 1945.

Oil and Gas Map of Illinois. By Alfred H. Bell and David H. Swann. Illinois State Geological Survey. Urbana, 1945.

On the Geochemistry of Tantalum. By Kalervo Rankama. Suomen Geol. Toimikunta, Bulletin de la commission géologique de Finlande, No. 113. Helsinki, September, 1944.

Paleontological Contributions. Memoirs of the Buffalo Society of Natural Sciences, Vol. XIX, No. 2. Buffalo, 1945.

Pennsylvanian Rocks and Fusulinids of East Utah and Northwest Colorado Correlated with Kansas Section. By M. L. Thompson. University of Kansas Publications, State Geological Survey of Kansas Bulletin 60, Part 2. Lawrence, 1945.

Petrographic Comparison of Pliocene and Pleistocene Volcanic Ash from Western Kansas. By Ada Swineford and John C. Frye. University of Kansas Publications, State Geological Survey of Kansas Bulletin 64, Part 1. Lawrence, 1946.

Published Maps. Compiled by P. J. Moran. Department of Mines and Resources, Mines and Geology Branch. Ottawa, Canada, 1945.

Reconnaissance Survey of the Headstone Mining District, Rio Arriba County, New Mexico. By T. D. Benjovsky. New Mexico School of Mines, State Bureau of Mines and Mineral Resources, Circular No. 11. Socorro, N.M., November, 1945.

Rock Wool. By E. M. Guppy and James Phemister. Memoirs of the Geological Survey; Special Reports on the Mineral Resources of Great Britain, Vol. XXXIV. Lindon: H. M. Stationery Office, 1945. Price, 9*d*.

Rosiclaire-Fredonia Contact in and Adjacent to Hardin and Pope Counties, Illinois. By Frank E. Tippie. Illinois State Geological Survey, Report of Investigations No. 112. Urbana, 1945.

The Search for Oil in South Australia. By Keith L. Ward. Geological Survey of South Australia, Department of Mines Bulletin 22. Adelaide: K. M. Stevenson, Government Printer, 1944.

Selected Bibliography on Coal in New Mexico. By Robert L. Bates. New Mexico School of Mines, State Bureau of Mines and Mineral Resources, Circular 8. October, 1943. Reissued February, 1946. Socorro, N.M., 1946.

Some Notes on the Archaeology of the Department of Puno, Peru. By Marion H. Tschopik. Expeditions to Southern Peru, Peabody Museum, Harvard University, Report No. 3; Papers of the Peabody Museum of American Archaeology and Ethnology, Harvard University, Vol. XXVI, No. 3. Cambridge, 1945.

Spurenelemente der Gesteine im sudlichen Finnish-Lappland. By Th. G. Sahama. Suomen Geol. Toimikunta, Bulletin de la commission géologique de Finlande, No. 135. Helsinki, 1945.

Stratigraphy and Oil-producing Zones of the Pre–San Andres Formations of Southeastern New Mexico. By Robert E. King. New Mexico School of Mines Bulletin 23. Socorro, N.M., 1945.

Stratigraphy of the Golden-Morrison Area, Jefferson County, Colorado. By L. W. LeRoy. Quarterly of the Colorado School of Mines, Vol. XLI, No. 2. Golden, Colo., April, 1946. $1.50.

Studien über die Ökologie und Geologie der Bodendiatomeen in der Pojo-Bucht. By Karl Mölder. Suomen Geologinen Toimkunta, Bulletin de la commission géologique de Finlande, No. 127. Helsinki, 1945.

Subsurface Geologic Cross Section from Ness County, Kansas, to Lincoln County, Colorado. By John C. Maher. University of Kansas Publications, State Geological Survey of Kansas, Oil and Gas Investigations, Preliminary Cross Section No. 2. Lawrence, 1946.

Subsurface Relations of the Maquoketa and "Trenton" Formations in Illinois. By E. P. DuBois. Petroleum Possibilities of Maquoketa and "Trenton" in Illinois. By Carl A. Bays. Illinois State Geological Survey, Report of Investigations No. 105. Urbana, 1945.

Subsurface Stratigraphy and Structure of Stones River Rocks in Northeast Central Tennessee. By J. B. Collins and R. Bentall. Oil and Gas Investigations, Preliminary Chart No. 3, Tennessee Department of Conservation, Division of Geology. 1945.

Suomen Geologinen Toimikunta. Bulletin de la

commission géologique de Finlande, Nos. 126, 128, and 132, each containing six to nine articles on various subjects. Helsinki, 1941, 1943, 1944.

Tektonik und Magma in der Insel Celebes und der indonesische Gebirgstypus. By H. A. Brouwer. Proceedings Nederl. Akademie van Wetenschappen, Vol. XLIV, No. 3. 1941.

Über das Grundgebirge des Kalantigebietes im südwestlichen Finnland. By Anna Hietanen. Suomen Geol. Toimikunta, Bulletin de la commission géologique de Finlande, No. 130. Helsinki, 1943.

Über die Erzgeologie des Viljakkalagebietes im südwestlichen Finnland. By Herman Stigzelius. Suomen Geol. Toimikunta, Bulletin de la commission géologique de Finlande, No. 134. Helsinki, September, 1944.

Valley Erosion since Pliocene "Algal Limestone" Deposition in Central Kansas. By John C. Frye. University of Kansas Publications, State Geological Survey of Kansas Bulletin 60, Part 3. Lawrence, 1945.

Viscosity Studies of System CaO-MgO-Al_2O_3-SiO_2. 1, 40% SiO_2. By J. S. Machin and D. L. Hanna. Illinois State Geological Survey, Report of Investigations 111. Urbana, 1945.